EXPERIMENTAL INVESTIGATIONS OF MEMBRANE FLUTTER AT LOW SPEEDS

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CERTIFICATE

This is to certify that the work 'EXPERIMENTAL INVESTIGATIONS OF MEMBRANE FLUTTER AT LOW SPEEDS' has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

In the present work experimental studies of membrane flutter with flexible boundaries at low speeds were made in the existing low speed (42 m/sec maximum airspeed), 3'x2', 3-dimensional wind tunnel at I.I.T. Kanpur. Effects of length-to-width ratio of membrane, size of membrane, inplane tension in streamwise direction alone and solid wall on membrane flutter were studied. Pressure survey over the membrane was made and its post-flutter behaviour studied. Rectangular, skew and triangular membranes made from canvas (0.06 cms thick) were studied by holding them at their corners only and with air flowing on both of its sides.

Travelling wave, large amplitude flutter of the membrane was observed. Critical speed, amplitude of oscillations and deflection of membrane was dependent upon its edge conditions. Width of the membrane had an important role in the flutter instability. Inplane tension raised the critical speed. Solid wall placed near the membrane lowered the critical speed. During post flutter, frequency of oscillations increased with rise in airspeed.

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LIST OF SYMBOLS

l	along flow dimension of the membrane (width in cms)
b	across flow dimension of the membrane (length in cms)
l/b	length-to-width ratio of the membrane
U	undisturbed free stream velocity (m/sec)
U_{cr}	critical airspeed (m/sec)
f	flutter frequency (c/s)
T	inplane tension (Kg)
C_p	pressure coefficient $(p-p_\infty)/\frac{1}{2}\rho U^2$
p	undisturbed airstream static pressure (Kg/cm^2)
p_∞	atmospheric static pressure (Kg/cm^2)
ρ	inside tunnel air density
T.E.	trailing edge
x-axis	along flow direction
y-axis	across flow direction

CHAPTER 1

INTRODUCTION

1.1 General

Flexible aerodynamic surfaces are formed mainly by a leading edge tension member, a trailing edge tension member and an inelastic membrane under inplane tension forming the skin. These surfaces being capable of stowing, find important application in aircraft and aerospace indusry. Parawings, flexible rotor blades, parachutes and perhaps inflated wings are few examples of flexible surfaces in aircraft industry. Paragliders are used in space vehicles satisfying few of the requirements of a recovery vehicle; especially the gliding characteristics required to make safe landing at low or moderate speeds. Hypersonic sails formed of flexible membrane (wooven wire cloth) seem to be one of the possible device meeting high speed vehicle requirements. Yachts are the historical example of flexible surface construction application.

Since the last decade there has been much interest in the theory of aerodynamics of these surfaces. The shape of these surfaces cannot be arbitrarily assigned; this arises from the necessity that the curvature of the flexible surface should balance the aerodynamic loads on it. So both dynamic and static conditions have to be satisfied to establish

aerodynamic characteristics of such surfaces. Most of the few investigators in this area have theoretically established the shapes of camber lines, aerodynamic loadings and gross aerodynamic characteristics of flexible surfaces in subsonic,[1] supersonic[2] and hypersonic[3] flow regimes. Few have made experimental investigations also of the aerodynamic characteristics of these surfaces at supersonic[2] and subsonic[4] speeds. In Ref. (4) gliders made of metal and porous fabric (nylon cloth) have been tested for their stability, control and performance characteristics.

It is established that for a particular combination of configuration and inplane tension there exists a critical dynamic pressure beyond which the membrane becomes unstable. Any disturbance picked up at this stage will change the equilibrium configuration of the membrane and the lifting surface is said to have developed flutter. Through the practical experience of sailors about sails and daily life observations; sails, flags and banners also have been found developing above type of instability. In skin panels this instability is confined locally over a portion of the skin exposed to air flow on one or both sides and spread over supports along edges or with intermediate supports, and the phenomenon is called 'Panel Flutter'. A membrane held between the taut or stiff edges can also be termed as 'panel' and the term panel flutter can be equally applied to them. The

mechanism of panel flutter is different from the classical flutter of aerodynamic (conventional) lifting surfaces where whole of the structure takes part in instability. Furthermore the phenomenon of membrane skin panel flutter is different from metal skin panel flutter in some aspects. Because of high flexibility of membrane and flexible moveable edges, it is quite likely that they may flutter at quite low speeds. It is observed in practice as well as established experimentally by P.F. Jordan[5] that a thin panel or a membrane skin (not too tightly strectched) developes flutter with travelling wave mode and the waves travel down stream. Few of the flexible surface vehicles such as sails or paragliders move or may have to move at quite low speeds and may encounter above type of flutter instability in their speed regime.

Under above circumstances, the flutter problem becomes flutter of a membrane at low speeds with moveable boundaries. So that the intended purpose of the flexible surface structures is not lost because of flutter development, it becomes necessary to investigate the possible cause of the flutter and study the possible measures that will avoid or delay it.

A survey of literature indicates that there has been very little experimental and analytical work on this problem. Nielsen[2] during his experiments, on evaluation of aerodynamic characteristics of flexible surfaces, has encountered membrane flutter at tension values less than those required for stable

shape of surface. Except for this, published experimental work on membrane flutter seems to be non-existent. S.Taneda[6] has done some experimental work on flutter of flags but it does not convey any relevant information on membrane flutter because the boundary conditions in his experiments were not that of a panel.

In view of the above, an attempt is made in the present work to conduct preliminary experimental investigations on membrane flutter of the aforementioned nature. Allowing air flow on either side of the membrane, the effect of several parameters viz. length to width ratio, size of the membrane, inplane tension and presence of solid wall near the membrane, on membrane flutter is also studied.

1.2 Literature Survey

In recent past many investigators have made both experimental and theoretical investigations on flutter of panels with standing wave type flutter motion. The panels were assumed to oscillate in their natural modes and the stability of these modes as a whole was investigated. The modes of a thin panel are readily influenced by the aerodynamic forces. Thus to study the stability of such skin panels, point to point stability of the panel modes has to be considered. When the approach of above investigators was applied to skin panels, the results showed that the sinusoidal modes are stable at all subsonic speeds but become unstable as soon as sonic speed

is passed. But experience has pointed other way. It is seen that a flag will flutter at quite low speeds and a skin made of thin paper will do the same if not stretched too tightly. On the other hand even if one excludes the stiffness of metal skin by holding a flag in supersonic stream the flag will remain stiff as a board and will not flutter. P.F. Jordan has given explanation of this paradox. He states that the flag when it flutters, does not exhibit the standing waves that the previously explained approach supposes, but it flutters forming travelling waves that travel along the stream. Jordan confirmed this by his experiments. In one case he held a sheet of paper at its leading edge and stretched it at its trailing edge by two weights, and a fabric (linen cloth) fixed to a frame in another case, in a low speed wind tunnel. As the tunnel speed was raised to critical flutter speed value (calculated theoretically by him) the paper and fabric panels exhibited travelling wave type instability. At higher critical speeds the wave length of flutter motion reduced and the frequency of flutter jumped to higher values. He further states that metal skins due to their higher Young's modulus, develope high stresses even for small amplitudes and even if critical flutter speed is surpassed, the high stresses limit the amplitude to small values to be almost unnoticeable. At higher critical speeds higher modes take over developing even smaller amplitudes. At sufficiently high speeds, any disturbance that

might arise is dissolved into smaller and smaller waves, and the result is a metal skin that gives the appearance of being stable. He finally concludes that a paper or fabric skin can develope flutter at low speeds with travelling wave motion. The critical speed increases with decreasing wave length.

Hedgepath, Budiansky and Leonard(7) have carried out theoretical analysis for periodically supported long panels assuming standing wave mode for flutter motion. J.W. Miles(8) has carried out travelling wave type analysis for thin infinite panels in subsonic and supersonic flows. The results of the two investigations do not seem to agree.

J. Dugundji, E.H. Dowell and B. Perkins(9) have made both experimental and theoretical studies on low subsonic flutter of long panels with flow on one side only. The panels were supported on elastic foundations at their leading edge and trailing edge and the two longer edges were kept free (free to move but were not flexible). In this experiment they have successfully noted the definite flutter of a travelling wave type character with waves travelling downstream confirming Jordan's results, though in their experiment there was small 'sticking' or 'standing wave component' present near the centre of panels in few cases. A theory of travelling wave flutter was also proposed by these authors accounting for their experimental observations. The agreement between the two was

good in respect of the flutter speed and wave length, though agreement was poor in respect of frequency and wave speed at flutter. This was attributed to some factors, like cavity below panel, boundary layer over panel and buffeting at trailing edge, which were not controlled in the experiment.

M.A. Sylvester and J.E. Baker[10] have carried out experiments on flutter of thin finite panels at M = 1.3. In few phases of their test runs the panels were left free at their longer edges parallel to airstream. Kappus, Lemley and Zimmerman[11] also have carried experiments at supersonic speeds on high amplitude panel flutter. In both these cases, the flutter observed was of travelling wave type and in the latter case the amplitude of motion increased towards trailing edge but not to a significant degree.

S. Taneda[6] has observed travelling wave flutter modes during his experiments on flags in a low turbulence, low speed, vertical flow tunnel. Flags of various materials, sizes and shapes were tested, in uniform flow, one sided flow and with splitter plates placed in the wake of fluttering flag. Flags started fluttering at low speeds in various modes viz. nodeless flutter, one node flutter, imperfect node flutter (amplitude not zero at node) and two node flutter, but in all cases motion was travelling wave type near trailing edge (see Plate 1). In nodeless flutter further there were two types of modes; (1) the three dimensional mode in which the waves at trailing edge moved

towards the rolled up (T.E.) corner and the 2 corners moved in nearly opposite phases. Which corner will roll up or how much will the phase difference be,has not been predicted definitely. (2) the two dimensional mode having higher frequency than the 3-dimensional mode and the two trailing edge corners moved in phase without any rolling up. Flag placed in one sided flow fluttered well in a travelling wave mode with frequency less than that of a flag placed in uniform flow but had non-symmetric wave motion due to non-symmetric velocity distribution on two sides of the flag (boundary layer modifies the velocity distribution over the surface). Splitter plates had little influence on flutter frequency and wave forms. The triangular flags were found to flutter well in two dimensional mode and had lesser flutter frequency and low flutter speed than equivalent length rectangular flags but had larger amplitude.

In Ref.(11) effect of flutter dynamic pressure penetration is studied. A slight increase in fundamental flutter frequency beyond flutter onset and increase in peak to peak amplitude of panel deflection, with larger amplitudes near trailing edge,is observed with increasing dynamic pressure penetration. S. Taneda also has observed increase in flutter frequency of flags with increase in freestream speed. It was observed that smaller the flag length, higher was the onset frequency.

Hanson and Levey[12] have done flutter investigations on some very low aspect ratio flat plates, in the range of Mach number 0.62 to 3.00. Two types of planforms with three different aspect ratios having same root chord, material and thickness and cantilever supported were tested. On comparing their experimental and theoretical flutter boundaries, the delta planform showed little change with aspect ratio except for lowest aspect ratio at higher Mach numbers. The clipped-tip-delta planform plates, however, exhibited considerable change in flutter boundaries with aspect ratio. For a given aspect ratio the clipped tip delta planform fluttered at lower dynamic pressure than the pure delta at all Mach numbers. The lower aspect ratio models fluttered at low values of dynamic pressure.

V. Sundararajan[13] has analysed the effect of presence of a rigid boundary placed parallel to an infinitely long finite width panel fluttering in inviscid flow and simply supported along the 2 longer sides. The panel is assumed to exhibit travelling wave type oscillation. For a given mass ratio and fixed width of panel, as distance of solid boundary from panel decreases, the critical flutter speed also decreases. The effect of solid boundary is considerable when it is quite close to panel. In the present work, experimental investigations are conducted to find whether the closeness of the wall has any effect on flutter of membranes.

Theoretical formulation of membrane flutter at low speeds with moveable boundaries has been done by Hanuman[14] using finite element techniques.

1.3 Objective and Scope of Present Work

Experiments have been conducted to study the membrane flutter at low speeds and effect of l/b ratio, size of membrane and inplane tension, on flutter are studied. Solid wall effects on flutter are also studied. Tests have been conducted in low speed (42 m/sec. maximum speed), 3'x2', 3-D, closed circuit wind tunnel. Various shapes of membrane (canvas cloth) have been studied.

Chapter 2 includes description of test programme, apparatus and experimental procedure adopted to study effects of above parameters.

Experimental observations are given in Chapter 3 and Chapter 4 contains discussions and conclusions of present work. In the end some suggestions are made to continue the experiments.

CHAPTER 2

2.1 Experimental Programme

With speed limitations of the existing wind tunnel in view, it was decided to carry out membrane flutter experiments at low speeds with following set of boundary conditions:

a) Leading and trailing edges fixed and longer sides free.

b) Leading and trailing edges flexible and longer sides free.

c) All sides free.

But for reasons explained in Section 2.4 only last set of boundary conditions i.e. moveable boundaries, was adopted for detailed studies.

Programme was also planned to gather information on effect of l/b ratio, size of membrane, inplane tension and solid wall presence on membrane flutter. During the tests only the particular parameter was made active to study its effect while others were kept fixed. Major part of the experiment consisted of testing rectangular shapes.

In rectangular membranes, some of the l/b ratios (2 to 8) were obtained by keeping constant length and changing the width while the rest (0.5 to 2) were obtained vice-versa. To obtain l/b < 0.5, some of the membranes were used by keeping their width along the flow. Various length width combinations were made to get same l/b ratio for size effect

studies. It was decided to make studies at four values of inplane tensions viz. $T_0 = 0$ kg., $T_1 = 5$ kg., $T_2 = 10$ kg and $T_3 = 15$ kg. Solid wall effects (wind tunnel horizontal walls in this case) on membrane flutter were studied at constant tension for fixed size rectangular membranes. The membrane was held at 10.2 cms. intervals along the height of test section during the tests.

With a hope to gain some information on the nature and initiation of flutter, pressure measurements were taken on upper and lower surfaces of the membrane at just before and just after the flutter onset. The limited span of pressure probe (see Section 2.2:5) was a factor in deciding the dimensions of above membrane. Post flutter behaviour was studied for two membranes of fixed size and held in the centre of test section. Airspeed was increased (penetrated) beyond onset speed and change in frequency noted.

Triangular membranes with apex facing the flow and base facing the flow were studied. Skew membranes having skew with stream direction and cross stream direction were studied. Both these shapes were tested in the centre of test section at tension T_1.

All the above tests were carried out at zero angle of attack with flow over both the surfaces of the membrane held in centre of test section. Flutter onset was decided visually, flow speed and flutter frequency at onset were noted. To obtain deflection and flow patterns during flutter, several

2.2 Apparatus

2.2:1 Wind Tunnel:

Flutter tests were carried out in the low speed, 3'x2', 3-D closed circuit wind tunnel in Aero. Engg. Dept. of I.I.T. Kanpur. The maximum speed of the tunnel was 42 m/sec. Airspeed in the tunnel was varied by changing the rpm of tunnel blowers through variable potentiometers. A grid work of 2 cm square was made on the facing vertical wall of the test section to facilitate observation of deflection and motion of membrane during flutter.

2.2:2 Membrane Fixture:

Points considered for the very design of the membrane fixture were:

(a) Least changes be made in the present test section.

(b) All types of boundary conditions be attained easily.

(c) Membranes of any dimensions could be held at any height.

(d) Ease in fixing the fixture.

The fixture (Plate 2) consisted of 4 mild steel bolts, 2cm. in diameter and 60 cms long with 25 cms long flanges fixed at their top end. Additional extension strips (Plate 2) could be fixed on these flanges to adjust the variations in dimensions of the membranes. The bolts were clamped to the floor of test section and the membrane could be held at any height in the test section. Models of various length were supported by placing the bolts at the appropriate location of the holes made in the floor of test section. Inplane tension could be applied by rotating the extension strips or/and supporting bolts about their own support points.

2.2:3 Test Membranes:

Various membrane models used in the tests were made from same stock of 0.06 cms thick canvas cloth. To avoid inconsistency in results, care was taken to cut all the membranes along one direction (length) of cloth sheet.

Models were mounted horizontally on the fixture at their four corners only (Plate 3) to get flexible boundaries. To avoid damage to the membrane due to cyclic contact with metals strips on lower sides and excessive pressure (if any) of the holding screws on the upper sides, it was separated by rubber washers on lower side and rubber and metal washers on upper side.

All the models were doped all along their four edges with 0.5 cm wide single coat. Small area around holes in the membrane was also stiffened with dope to avoid yielding of fabric along holes during flutter. A specimen of the test membrane is attached herewith.

2.2:4 Arrangement to Apply Tension:

It was not possible to design a force system which could directly induce inplane tension in the membrane during continuous running of tunnel. Hence indirect method was adopted to induce tension in the streamwise direction only. The method consisted of following:

Know before hand the extension in each membrane corresponding to each value of tension. Then apply the same extension in the corresponding membrane to obtain the desired tension during the runs.

For calculating the extensions, load deflection curve (Fig.1) for membrane material (canvas cloth) was obtained on Instron Testing Machine. The results of above curve are valid only when the load application is uniform across the width. To apply nearly uniform tension during runs it was decided to hold the membrane in wind tunnel at its leading edge and trailing edge (Plate 4) and stretch, but had to be dropped for reasons explained in Sec. 2.4. Hence the method given below was adopted.

Each of the membrane was held separately, on a rig at its nominal dimensions, in a manner similar to mounting in wind tunnel (Plate 5). Corresponding loads were applied on each model and extensions so occurred recorded and then used during test runs. After unloading, the original length of the membrane was not regained due to setting of the fibres. Thus the nominal dimensions of the membrane were changed slightly. But this was taken care of while applying the tension during tests.

The process anyhow had the advantage of simulating exact conditions of the wind tunnel mountings. This type of loading did have nonuniform distribution of tension across the width but had to be adopted because of tunnel limitations.

2.2:5 Pressure Probe:

Plate 6 shows the traversing arrangement for the pressure probe. The traverse was mounted on the top wall of test section. The existing top of the test section was replaced by another wall having two slits, 1 cm wide and 45 cms apart. Plate 3 shows the pressure probe, fabricated in accordance with the specific needs of the present work, held over the uppter surface of the membrane.

To enable traversing on either side of the surface while the tunnel is running, the probe was made in two parts. The left part (viewed along stream) 21.0 cms long contained 4 tubes, of 1/16" dia and 5 cms length, fixed 5 cms apart and the right part 19 cms long contained 3 similar tubes. These parts were joined separately to two vertical stems which were clamped in the traverse gear. To shift the probe from one surface to the other, the two parts were disengaged and rotated about their own clamps in the traversing gear such that the tubes cleared the membrane. They were then lowered or raised to desired distance and rotated back to lie in a straight line. The two parts after disturbing could be kept in a line making one piece by holding them through a cylindrical 'C' clamp fixed at the end of bigger limb. A maximum span of 40 cms thus could be covered with the pressure probe. A 1/64" through hole, 2cms from tip, was made in each of the 7 tubes thus making static pressure tubes. A total head tube of the same dia was also fixed below the central tube of the pressure probe to have information about the flow over oscillating membrane.

2.3 Instruments

i) Speed and Pressure Measurements

2.3:1 Manometer: A veriable inclination multitube manometer using distilled water as the working substance was used to take pressure readings. It was provided with freezing mechanism to arrest the readings. The tunnel being closed circuit, static temperature of airstream at start of each set of readings was measured with alcohol thermometer placed at the downstream end of test section. Temperature corrections were thus applied for inside tunnel air density to calculate the speed of flow and coefficient of pressure (C_p).

ii) Frequency Measurement:

Various instruments were tried to measure flutter frequency. Experimental set up, procedure and difficulties associated with each of them are described below:

HOT WIRE PROBE TECHNIQUE: A single wire hot wire probe was placed at a point below the bottom surface of the membrane where maximum aplitude was expected during flutter. With a view to get least interference of the main stream and maximum influence of vertical fluctuations, the wire of the probe was kept parallel to the main stream and perpendicular to the flow component induced by fluttering membrane.

2.3:2 Hot Wire Anemometer and Oscilloscope: The output of the hot wire probe was fed to Tektronix, Type 545 B, Oscilloscope through DISA , Model 55 A 01, Constant Temperature Hot Wire Anemometer. It was decided not to rely upon oscilloscope

records because after flutter onset the wave forms did not repeat periodically. The wave forms were distorted and changed shape with time. Thus making direct frequency measurements difficult. To get simultaneous records, photographs of oscilloscope records were taken at different times. Few of them are shown in Plate 7. But again the non-repeating distorted wave forms were observed. Thus hot-wire anemometer-oscilloscope combination was not used.

2.3:3 Hot Wire Anemometer and Wave Recorder: To have continuous record of variation of wave forms observed above, Type 1910-A, Recording Wave Analyzer was used and anemometer output was given to it. This combination also did not show any favourable results. One set of records is reproduced in Plate 8.

Presence of non-repeating distorted wave forms having multiple peaks, gave the indication that main stream fluctuations had some influence on vertical fluctuations of the flow due to membrane. Because of uncertainity in magnitude of amplitude during flutter, optimum distance of probe from fluttering membrane could not be established. An attempt was made to keep the probe very near the membrane to reduce main stream effects, but the wire broke because of shock due to uncontrollable oscillations of the membrane. Wind tunnel test section turbulence level was then measured with and without membrane supports. The values are 1.08% and 0.85% respectively which may be taken as ineffective compared to large fluctuations caused by the membrane. Thus hot wire probe technique was dropped.

STRAIN GAUGE TECHNIQUE: Change in strain in membrane during flutter motion was employed for frequency measurements. To measure change in axial strain, a single SR-4 strain gauge with gauge factor 1.96 was located on upper surface of the membrane at mid span at about 1/4 from trailing edge. The leads of the strain gauge were routed along downstream direction. Because of large amplitudes of deflection at this position and downstream side pulling of leads by the drag, the leads came out quite frequently at the joints of the strain gauge. The location of strain gauge was then changed to about 1/3 from leading edge with leads taken in upstream direction. At this location the amplitude was not as high as at trailing edge but was of appreciable magnitude for the strain gauge to sense. At this location the leads stayed for much longer time. The strain gauge output was fed to recording equipment through strain indicator.

2.3:4 Strain Gauge and Oscilloscope:

The output from strain indicator was given to the oscilloscope. Change in strain could be distinctly observed on oscilloscope. At flutter onset there was substantial change in strain gauge output with wave forms becoming comparatively smoother. This helped in deciding flutter onset also. Here also non-repeating wave forms were observed. Though frequency could be counted by triggering the oscilloscope signal but out of 4 or 5 triggers hardly one gave the

necessary information. And hence the method being unsatisfactory and unreliable was abandoned.

2.3:5 Strain Gauge and Electronic Counter:

Electronic counter essentially counts the number of events occurring in a particular time and gives a digital display. The strain indicator output was given to type 521-C Hewlett Packard Electronic Counter which had an input requirement of 0.2 volts rms minimum. In the beginning of this method there was no signal given by the counter even at its maximum sensitivity setting. It was verified (through power amplifier) that the output of strain gauge was too small. A voltage amplifier having a gain of 20 was used to amplify the strain gauge output and thus readings could be obtained in counter. But even then the information was unreliable. For different sensitivity settings of the instrument different frequency indications were displayed. Further during a particular span of time the readings on counter changed continuously after each count, though the scatter was not much. With this observation it was expected that at different sensitivity settings, because of the nature of wave forms recorded earlier, the small superimposed peaks also became strong enough to pass the threshhold limit of the instrument and gave counts and thus the change in readings. These superimposed peaks being character of the membrane behaviour during flutter, could not be avoided and correct setting of sensitivity, which could have been different for different modes, could not be sought out. Thus using electronic counter for frequency measurements was also not possible.

2.3:6 Strobotac:

After all these above instruments failed to serve the purpose satisfactorily, type 1531-AB Strobotac was used successfully to measure flutter frequency.

After flutter onset was decided, the strobotac was flashed on the membrane and starting from its highest setting brought to lower setting slowly till 1st single image of the membrane (dots were marked on membrane for easy vision) was obtained. The reading on the dial at this setting gave the frequency in cycles/minute.

2.4 Experimental Procedure

To have the 1st type of boundary conditions, membrane was held at its leading and trailing edges by aerofoil shaped strips (Plate 4). Airflow speed over the membrane was raised gradually. But no instability of the membrane occurred even at maximum speed of the tunnel.

To obtain the flexible leading and trailing edges, the two edges were held with the help of thin mild steel wires. In this case because of relaxation of boundaries, the flutter occurred at some speed. But the wires restricted the motion of the flexible leading and trailing edges during flutter. The wire at the trailing edge failed quite frequently during flutter due to fatigue caused by excessive oscillations there. When the wires were tightened in an attempt to avoid the breakage, the critical speed again fell beyond the tunnel range.

Third type of boundary conditions were then tried. All the four edges were kept free and the membrane was held at its four corners only. At some value of the airspeed, there developed a scoop type bulge near the leading edge portion. This disturbed the flow over rest of the membrane and no instability occurred even at sufficiently high speed (compared to critical speed in second type). Whole of the membrane was then stiffened with single coat of dope to avoid the unwanted leading edge bulge formation. The purpose was served this way, but there was no flutter till maximum speed of the tunnel. The membrane almost behaved like a foil because of modification in its flexibility characteristics. Thus to continue the investigations, it was decided to stiffen only the sides of the membrane so that apparaently there is no change either in the membrane flexibility or modification in the boundary conditions. This could be achieved by doping all the sides of the membrane with a single coat of it. Doping the edges served a secondary purpose of avoiding the coming out of fibres. These boundary conditions were thus carried on.

Since it is difficult to determine precisely a sharp point at which flutter begins, it is a reasonable convention to specify flutter onset within about 10% of the dynamic pressure. Flutter onset in the present case was decided visually by increasing the air stream velocity over the membrane in increments until significant vibrational activity was observed over the membrane.

For ease in frequency measurements, coloured dots were marked on membrane some distance apart along the centre line.

In deciding the single image setting of strobotac to be correct, the moving wave was also simultaneously made stationary (in some cases, to move at slowest possible rate) by changing the strobotac setting if required. To further ensure this result, the strobotac was set at some multiple of this setting. Appearance of that many multiple images of one dot with wave having slowest possible motion confirmed the 1st setting and thus indicated flutter frequency. At times it was not possible to exactly get single image of the membrane or stationary waves. In few cases these could be obtained over a range of strobotac setting thus giving the frequency in a range rather than a defined value. By freezing the moving membrane with strobotac, number of peaks formed during motion, their shape, size and nature was noted. Still photographs of the stationary made fluttering membrane were taken with Nikkon camera using high speed films. Records were taken with 16 mm, H 16 Rex Model, Paillard-Bolex movie camera but could not be presented since the development of the film could not be arranged in time.

For speed calculations, the undisturbed flow total head was measured as average of several total head tubes placed in settling chamber. The undisturbed flow static head was measured through a flush wall tapping located a short distance upstream of test section entrance. These 2 tappings and 8 tappings from pressure probe were connected to the multitube manometer. During flutter the readings in the manometer tubes fluctuated much. To note the readings in all the tubes at the same time,

the readings were arrested. Due to inefficient mechanism there was a depression in fluid column in all the tubes during freezing. The amount of depression varied with level of rise of the fluid. To have all time history of pressure fluctuations, movie records were tried. Because of the difficulty in their acquisition, mean values of the fluctuating readings were recorded.

To study inplane tension effect, the membrane was mounted in the wind tunnel and corresponding tension applied to it as explained in Sec. 2.2:4 and Sec.2.2:2. The speed was increased till flutter occurred and necessary readings and observations were noted.

During post flutter studies, speed of air was increased gradually till flutter occurred. The critical flutter speed and frequency noted. The speed was then raised in increments and held constant for sometime. The manometer readings and strobotac readings were noted at each interval of speed and the wave nature also noted. It was decided to conduct this test for both the membranes at tensions T_1, T_2, and T_3 but could be carried out at T_1 only because the membrane tore out at trailing edge during deep penetration.

Wall effect and pressure survey were carried out at tension T_1 for two membranes, by holding them at the desired height. The just-before-onset condition for pressure measurements was chosen as appearance of one sudden jerk. At

this speed, pressure readings above and below the surface of the membrane were taken as explained in Sec. 2.2:5. Speed was then increased very gradually till flutter developed. Set of pressure readings was completed as before. All the times during pressure survey, probe was kept 5 cms above or below the undeflected position, and traversed along length of membrane with 5 cms interval.

Triangular and skew membranes were tested at tension T_1 with usual procedure.

2.5 Flow and Deflection Pattern Visualisation

Few methods tried for visualisation are given below.

(a) Flow Visualisation

2.5:1 Smoke Generator:

A smoke streak was made to flow through a series of tubes held parallel to the membrane near its leading edge. But the smoke streaks disappeared completely in a short distance ahead of their outlet even at quite low speeds which were much below the flutter speed.

2.5:2 Titanium Tetrachloride ($TiCl_4$):

Liquid $TiCl_4$ was poured along the span at leading edge of the membrane as an alternative for generating smoke. But the fumes were exhausted by the time sufficient speed could be attained or flutter could occur.

Smoke visualisation techniques seems to be useful at low flow speeds. At high speeds the smoke outlet velocity should

be increased, perhaps by generating smoke under pressure or by increasing the capacity. An apparatus which can pass $TiCl_4$ in controlled quantity and at desired time would help in second case.

(b) Deflection Pattern

2.5:3 Ink Spray:

For mode shape visualisation ink was sprayed over the fluttering membrane through a single flexible tube having a glass nozzle at its outlet. Because of porosity of the canvas, the ink was soaked when and where it fell and did not follow any deflection pattern as it could be expected if the membrane were non-porous.

CHAPTER 3

EXPERIMENTAL OBSERVATIONS

Wind tunnel tests have been carried out on various shapes of membrane with the aim of studying the flutter phenomenon and effects of various parameters on it. Behaviour of membrane as observed under various conditions is explained in present chapter. Still photographs taken during flutter motion are shown. In addition pen sketches* representing the flutter phenomenon only qualitatively, have been made wherever found necessary.

3.1 Membrane Behaviour During Flutter:

From start of air flow to the time of development of instability, significant changes that occurred in the membrane were observed visually. Its behaviour during flutter and post-flutter stages was studied with strobotac. This section contains description of nature of flutter, flutter development, and wave propagation and wave shapes.

2.1:1 Nature of Flutter:

Experiments conducted show that the flutter of the membrane with moveable boundaries is a travelling wave flutter with waves moving downstream. The flutter instability had some common

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*	numbers put in braces indicate figure to be referred in the corresponding sketch.
-.-.-.-.-	line indicates undeflected position of the membrane
————	line indicates position of the membrane after deformation
-------	line indicates oscillations of the membrane

features in all the membranes under study.

During flutter development, all membranes had small amplitude oscillations at start of air flow which changed to increased amplitude irregular oscillations as the flow speed increased. Below the critical speed, membranes deflected into some shape and kept oscillating about it with casual jerks. Just after this, at a slightly higher speed, few sudden jerks appeared and set the apparently regular travelling wave flutter in the membrane.

Plate 9 typically shows the generation, nature and propagation of waves during motion. The waves generate at leading edge portion having small amplitude and move towards trailing edge with increase in their amplitude during downstream movement. This plate also shows that deflection of membrane increases towards trailing edge. This was observed in all the membranes but degree of increment of deflection was different in different cases.

Observations indicate that within the present range of tests, flutter instability once occurred did not die out even after increasing the speed. This may be due to the limited range of speeds available in the tunnel. This has to be verified by further experiments. The observations also indicate that in the range of speeds at which the experiments are conducted, flutter is not catastrophic.

3.1:2 Flutter Development Phenomenon:

Depending upon the shape and size of membranes, the flutter developed in them with slight differences.

Rectangular Membranes

In rectangular membranes three types of behaviour during flutter development was observed.

(1) (Refer to Sketch No.1) At low speeds, membrane moved up and down with respect to undeflected position in some shape but all the time accompanied by small amplitude oscillations$_{(i)}$. At slightly higher speeds, the membrane stayed up or down and kept oscillating about this position$_{(ii)}$ with increasing amplitude of oscillations. At further higher speeds there appeared a small smooth bulge (up or down) near the leading edge portion and consequently a larger but shallow bulge over rest of the portion$_{(iii)}$. As the speed was increased further, the bulge at trailing edge portion started getting pushed downstream thus reducing in size and simultaneously the size of leading edge bulge increased with very little increase in its peak. The membrane continued oscillating about this deflected shape even when the bulges moved downstream$_{(iv)}$. The oscillations grew irregular with increase in their amplitude and rate. After this at some speed, size of trailing edge bulge reduced appreciably and there appeared casual jerks in the membrane reversing its deformed shape (peak to valley and vice-versa). At a speed slightly above this, occurrence of few sudden jerks set the membrane into apparently regular oscillations which exhibited

travelling wave motion. This speed may be called the flutter onset speed or simply 'Onset Speed'. Generally this behaviour was observed for l/b >2. Plate 10 shows the behaviour just before onset and Plate 11 shows number of bulges (three) formed in the same membrane.

In some membranes having l/b near 2, but with smaller length, unlike the previous step there were formed two bulges of almost equal size$_{(v)}$. There was no backward movement of these bulges. Rest of the changes were same uptil onset speed at which the bulges reversed their nature with jerks. Just above this speed, increased rate of reversal of deflection shape set the flutter.

(2) Second type of behaviour (Sketch No.2) was observed for l/b 0.5 to 2.0. At start of flow, in some cases membrane stayed up or down and had small amplitude oscillations about this shape$_{(i)}$. In few other cases the membrane moved as a whole about the undeflected position at very slow and gentle rate$_{(ii)}$. Oscillations grew irregular and faster with increase in speed over a range. At some speed casual jerks appeared and the single bulge dissolved into a shape$_{(iii \text{ or } iv)}$. This shape stayed for short time only and appearance of another jerks brought it back to single bulge. With increase in speed after this step, occurrence of jerks changed the irregular motion of membrane to apparently regular travelling waves and thus setting the instability on.

(3) Sketch No.3 corresponds to flutter development in membranes having $l/b \leq 0.5$. A slightly different phenomenon was observed here. In the beginning there was small amplitude mild flipping of whole of the membrane$_{(i)}$ or part (generally portion near the leading edge) of it$_{(ii)}$. With increase in speed the flipping changed to apparently regular small amplitude rotary oscillations$_{(iii)}$ having the node approximately at $x = l/2$. These oscillations grew in amplitude and rate with increase in speed but remained almost regular. At some speed (which was appreciably less compared to onset speed in previous cases) these oscillations suddenly changed into regular travelling wave motion. The membrane developed the instability without giving any prior information of onset speed unlike in previous cases.

Skew and Triangular Membranes

Skew and triangular membranes developed the instability in the second manner with a slight difference. In the beginning they had motion as shown in (ii) of Sketch No.2. With increase in speed the membrane stayed up or down and behaved like (ii) of Sketch No.1 but with comparatively faster oscillations. Just at the onset speed a jerk disturbed the shape and membrane started exhibiting travelling wave type motion.

3.1:3 Wave Propagation and Wave Shapes:

In all types of membranes, waves propagated downstream towards trailing edge but the wave characteristics were different in different membranes.

Rectangular Membranes

(1) In membranes having $l/b \geq 2$ the wave shapes were quite regular and shallow. Number of bulges formed ranged from two to three for different length width combinations, but all the times the wave length was large as shown in Plate 12 and Sketch No.4. For fixed length, a slight increase in wave length with increase in l/b ratio was observed.

(2) Membranes with $1 < l/b < 2$ developed two types of wave forms. In 1st type, there developed a small crest or trough near the leading edge and a large and deeper trough or crest respectively over rest of the portion of membrane (Plate 13). Second type of wave formation was observed in membranes having $l/b = 1.5$ with sides as 60x40 and 45x30. In this case almost three bulges were formed having amplitude and wave length comparable to each other but their amplitude was large compared to case (1). The wave shape pattern over the membrane during propagation is shown in Plate 14 and Sketch No.5. For fixed width, longer membranes had slightly larger wave length.

(3) In membranes lying between l/b 1.0 and 0.5, the bulges were of comparable size (in peak and wave length) among themselves (Plate 15), but the bulges were smaller in wave length and slightly bigger in peak than in type second of case (2) above. During propagation there was small increase in the wave length and amplitude of bulges. The waves moved with their crests or troughs almost parallel to y-axis and diffused at their ends as they reached near trailing edge (Sketch No.6). Few membranes

among $l/b = 1$ developed two bulges but their motion was like shown in Sketch No.6. In above cases, that how many bulges will be formed was not sure.

In membranes having $l/b < 0.5$, waves formed were parallel to y-axis and bulges were much deeper (Plates 16 and 17). In these cases by the time one wave generated at leading edge, the previous one had almost vanished at trailing edge. So whether or not there was increase in the wave amplitude during propagation could not be noted with surety. Plates 17 and 18 show the wave shape at trailing edge side for $l/b = 0.125$ membrane. There is folding up of the downstream side of trailing edge bulge in the upstream direction.

Skew Membranes

In skew membranes, waves moved along their longer diagonal.

In cases when skew was with cross stream direction, the behaviour of wave from its generation at leading edge to its finish at trailing edge corner is explained in Sketch No.7. Small arrows there show direction of motion of waves. Ratio of amplitude of wave at leading edge to its amplitude at trailing edge was approximately equal to 3.

When skew was along streamwise direction, the waves formed at leading edge and moved along x-axis for a short distance and then drifted slightly towards trailing edge far corner as shown in Sketch No.8. Peak amplitude ratio in this case was

reduced to about 2.

Drift in wave propagation was less in the membrane having lesser skew angle.

Triangular Membranes

Triangular membranes exhibited relatively regular behaviour than other types of membranes. The waves propagated smoothly downstream with wave forms exactly sinusoidal.

Plate 19 shows the increased amplitude at trailing edge and wave propagation for a triangular membrane with base facing the flow. During wave propagation whole of the membrane moved with snake like motion in the vertical plane. Wave form and deflection mode for the above orientation is shown in Plate 20 and arrows marked in it indicate direction of motion of waves.

Plate 21 shows the wave form for case when apex faces the flow. Here the waves generated along the slant edges, moved towards centre line as shown by arrows in Sketch No.9(a) and met there forming a crest or trough along the central line as shown in Sketch No.10. The peaks changed their nature from positive to negative with sudden jerks. The slant edges of the membrane looked oscillating about a horizontal plane as shown in Sketch No. 9(b) with nodes at the support points.

From Table (1) it is seen that skew membranes when placed with skew along streamwise direction, had lower critical speed and higher onset frequency compared to when the same

membrane was placed with skew along cross stream direction. Likewise triangular membranes when placed with base facing the flow had lower critical speed and higher onset frequency than when placed with apex facing the flow. Further, smaller the size in any case, lower was the critical speed and onset frequency.

Triangular flags in Ref. 6 were found to flutter at low speed and low frequency compared to equivalent length rectangular flags. In the present case base facing the flow triangular membrane represents a flag whose trailing edge is constrained. Here it has got higher flutter frequency but lower critical speed compared to equivalent length rectangular membrane.

3.2 Membrane Deformation Modes.

The deformation of the membranes was in accordance with the wave forms developed in them. To get the deformed shapes, fluttering membrane was made stationary with strobotac and its image made on the grid work in some cases. Photographs of membrane and its image were taken (Plates 22 and 11). At times for ready reference, deflections were noted from the grid work directly.

Deformation of membranes having $l/b > 2$ was shallow and is shown in Plates 22 and 11. The deformation of membrane was more towards trailing edge except for small length in $l/b = 2.0$. Plate 12 shows deflection pattern corresponding to wave shape shown in case (1) of Sec. 3.1:3. In some cases when b was ≤ 7.5 cms, the membrane deflected forming two bulges but

the deflection was still shallow.

Plate 13 shows deflection behaviour of membranes corresponding to 1st type of wave shapes in case (2) of Sec. 3.1:3. The deformation at the trailing edge was of appreciable magnitude compared to that at leading edge. Plate 14 and Sketch No.5 show the deflection corresponding to 2nd type of case (2) of Sec. 3.1:3.

Deformation modes in membranes having l/b around 1.0 and 0.5 are shown in Plates 15 and 17 where former shows slight increase in deflection at trailing edge and latter shows large deflection of whole of the membrane.

No distinct deformation modes were observed for membranes having very low l/b ratio.

Deformation modes of skew and triangular membranes have been explained or shown in Plates in Sec. 3.1:3.

In the present range of speeds, chess board type deflection pattern, as concluded by Jordan (Ref.5) as character of deflection of membrane in travelling wave flutter, was not observed on any of the rectangular membranes during present experiments. This may be because of free sides of the membrane or higher critical speeds not reached due to limited speed of the tunnel. This may be verified by further detailed experiments.

Triangular flages studied in Ref.6 had larger deflection compared to equivalent length rectangular flags. In present case because of restriction at the trailing edge, the triangular

membranes had smaller deflection compared to equivalent length rectangular membranes. Like in Ref.6, trailing edge attempted to fold up here also (Plate 20) but was restricted being fixed.

3.3 Effect of Various Pramaeters:

Quantitative effects of l/b ratio and membrane size on flutter will be discussed in next chapter. Apparent effects of inplane tension and solid wall are explained here.

3.3:1 Inplane Tension:

Only rectangular membranes have been studied for inplane tension effects with tension applied in the streamwise direction alone.

Phenomenon of flutter development, wave propagation and wave forms remained apparently unchanged at all values of inplane tension. But wave amplitude and hence deflection of the membrane was less at higher tensions and the decrease was more for bigger membranes. As an example, membrane 80x40 had 26 cms to 28 cms peak to peak amplitude of waves at trailing edge at T_0 and it reduced to about 20 cms at T_1. In others, the decrease was not as large as to be noted distinctly. The crtical flutter speed was higher at higher tensions with corresponding increase in onset frequency.

3.3:2 Effect of Solid Wall:

As distance of the solid wall from membrane decreased, the critical speed and frequency also reduced. Flutter development was almost same at all distances from wall. There was slight increase in wave length with bulges becoming smoother near the

wall. The bulges formed in 20x30 membrane when held in centre of the test section were almost parallel to y-axis but were not smooth. As the membrane approached the wall the shape of bulges became smoother and diffusion at their ends increased. Figure 8 shows the fall of critical speed and flutter frequency with distance from solid wall. Amplitude of oscillations was also slightly less near the wall.

3.4 Pressure Survey

During pressure measurements over the membrane, line joining the level of fluid column in manometer tubes closely followed the deflected contour of cross-section of membrane at that station. At before onset condition the membrane had small upward deflection of the trailing edge portion. When the pressure probe was traversed over this portion, at points where the distance of probe from membrane was very small, the membrane started fluttering. As soon as the probe was taken away or distance became large, the instability disappeared. Change in readings of total head tube of pressure probe observed over the oscillating trailing edge portion gives an indication of irregular flow there.

3.5 Post Flutter Behaviour

The two membranes were kept oscillating at T_1 for about 30 minutes and 10 minutes corresponding to about 43000 cycles and about 27000 cycles respectively. Both the membranes tore out at trailing edge corner because of excessive and strong oscillations there during deep penetration. Plate 23 shows the motion of a torn membrane and Figure 9 shows the variation of frequency

with incrcase in speed.

The wave form and wave shapes remained apparently same during penetration but the amplitude of oscillations was more at higher speeds compared to amplitude at low speeds.

CHAPTER 4

DISCUSSIONS AND RESULTS

4.1 Discussions

Studies in previous chapters have clearly indicated that membrane flutter is of travelling wave type unlike what is observed in streamlined bodies like wings or in metal panels in some cases. Some distorsion of travelling waves from a sinusoidal shape was observed in membranes lying around l/b 1.0 to 2.0. The amplitude of oscillations was large during flutter. Analysis of this type of membrane flutter problem is therefore relatively complicated and requires further investigations.

Figures 2 to 5 present critical speed and flutter frequency for rectangular membranes as function of inplane tension and l/b ratio for constant length and width combinations. These figures and few others indicate that frequency during flutter motion behaves in accordance with speed in almost all cases. Some scatter or deviation in the frequency trend is there at times. This may be because of the strobotac difficulty. More improved techniques to determine the frequency will help to reduce the scatter. Table (I) contains critical speed and flutter frequency values for skew and triangular membranes studied under present work.

The experiments show that flutter development and amplitude of oscillations depend upon several factors like

edge conditions, size of membrane and inplane tension along with speed of flow.

4.1:1 Effect of Edge Conditions:

Previous chapter shows that the membrane had taken a curved shape before the onset of flutter. Due to this deflection, inplane tension will be induced in the membrane which will increase its stiffness and consequently the critical speed. Same phenomenon need not necessarily happen if the edges are stiffened. As an example, 1st set of boundary conditions when tried, there was no flutter of the membrane even though there was apparently hardly any curved shape taken by it. But because of the clamped edges, a slight deflection of the membrane will induce large tension in it and thus it requires high speed to develope the instability.

Edge conditions apart from influencing critical speed, restrict the amplitude of oscillations also. Membrane with 2nd type of boundary conditions had higher critical speed than the one having 3rd and adopted set of boundary conditions but the amplitude of oscillations was small in former type.

4.1:2 Effect of Dimensions:

l/b Ratio of Membrane

Figures 2a to 5a show that the critical speed decreases with increase in l/b ratio over 1 to 2 whereas it increases with l/b from 2 to 8 and $l/b < 1$.

It may be noted that from l/b 1 to 2, width of the membrane was kept constant. For a fixed width, length of the membrane was thus more at higher l/b. Larger membranes in above range of l/b have been observed developing larger waves, which have got lower critical speed (Ref.5). Hence as l/b increases for fixed width, the critical speed reduces.

In membranes having $l/b < 1$, width was kept same but unlike in above case, critical speed decreases as l/b decreases. In this range of l/b cross stream dimension of the membrane is larger than its streamwise dimension. This relatively large dimension makes the membrane flexible along its direction. Also case (2) of Sec. 3.1:2 shows that these membranes (around $l/b=0.5$) had developed very small curved shape before flutter and consequently a small tension will be induced. These two effects together make the membrane flutter at lower speeds. Further as l/b reduces below 0.5, the membrane behaves like one body along flow direction (see case (3) of Sec. 3.1:2) and thus inplane tension induced due to flow disturbance will almost be negligible. This along with relatively high flexibility in cross stream direction will make the smaller l/b ratio membranes flutter at still low speeds.

$l/b \geq 2.0$ were achieved by varying the width over constant length of the membrane. Section 3.1:3 shows that the wave length in this range of l/b was slightly higher than that in l/b 1.0 to 2.0. Membranes having $l/b > 2.0$ thus may be expected to have still lower critical speed. This is opposite to what is

observed. In the above catagory of l/b, because of lesser width at higher l/b, the membrane becomes stiffer across the flow and the larger length will develope a larger curved shape which induces large tension and as a consequence of these two effects, critical speed will be higher at higher l/b ratios in this range.

The observations indicate that the cross stream direction (width) of the membrane plays an important role in the flutter instability. Also this section shows that the variation of critical speed with l/b ratio depends upon the manner in which it is achieved.

Points encircled in Figures 2 to 5 correspond to membranes having very small l/b. They started fluttering at very low speeds. Because of the ineffective control of wind tunnel at low speeds, the air speed could not be held constant at onset speed. Readings thus generally were taken with tunnel speeding up. It seems that small changes in air speed have got great effects on the critical speed and frequency in the vicinity of flutter and the effect remains to be studied under better control of speeds.

Size of Membrane

Figures 6 and 7 are drawn showing variation of critical speed with width or length of the membrane for constant l/b ratio.

Critical speed increases as the size ofthe membrane reduces for same l/b ratio. In the present range of tests, rate of increase of critical speed with reduction in size is almost constant for l/b 0.5 whereas for l/b > 1.0 it becomes faster

as the size of the membrane becomes smaller and smaller.

Flexibility of a membrane will be same when placed with width or length along flow direction but the critical speed is not same. For example, 10x20 membrane flutters at 19.00 m/sec at T_o but when placed as 20x10, it does not flutter even at 35.80m/sec at T_o. Another membrane 22.5x15 will have slightly higher flexibility than 10x20 or 20x10 membrane. It flutters at 24.50 m/sec which of course is less than $(U_{cr})_{20x10}$. But when it is placed as 15x22.5, critical speed is 19.50 m/sec which is less than $(U_{cr})_{22.5x15}$ but is greater than $(U_{cr})_{10x20}$. Similar behaviour is exhibited by 20x30 and 15x30 membranes. Here also this is against expectation behaviour. This may be because of larger dimension of the membrane in the flow direction which can take large curved shape and thus induce tension in it and hence higher critical speed.

This means that the aerodynamic forces have great influence on the orientation of membrane and on its cross stream dimension. For $l/b < 1$ there seems to be some interaction between aerodynamic forces and structural stiffness in such a way that less stiff membrane flutters at higher speeds. More detailed experimental investigations are needed for clear understanding.

4.1:4 Effect of Inplane Tension:

Figures 2a to 5a show that as inplane tension increases the critical speed also increases. Broken lines in Figures 6 and 7 show the rate of increase of critical speed with tension. Flutter frequency also increases with increase in tension though not with

a definite relationship but is in accordance with increase in speed.

Tension induced in the membrane reduces its deflection and limits the amplitude of oscillations.

4.1:5 Effect of Solid Wall:

Variation of critical speed and flutter frequency with distance of the membrane from a solid wall is shown in Figure 8.

In Ref. 13, solid wall effects have been analysed for an infinitely long finite width panel. Whereas in the present work situation is much different along with different boundary conditions. The results of present studies thus cannot be compared quantitatively with that of Ref. 13 but on qualitative comparison they seem to agree with each other. Figure 8 shows that the critical speed decreases as the membrane approaches either of the walls of test section.

Figure 10 shows change in pressure distribution over the lower surface of 45x30 membrane before flutter when placed in the centre of test section and 10.2 cms below the top wall. Variation of C_p along length of the membrane is almost following its deflected shape. Decrease in C_p values and change in its distribution near the wall indicates modification and decrease in deflection of membrane due to solid wall.

4.1:6 Post-Flutter Behaviour:

Figure 9 shows that frequency of oscillations increases when the air speed over a membrane is increased beyond onset speed.

Smaller of the two membranes has got higher onset frequency in accordance with Taneda's (Ref.6) observation on rectangular flags. A point of interest may be the larger membrane in this case. It has got dimensions (40x25) very much close to l/b=1.5 (45x30) but the observed onset frequency of the former is much lower than that of the latter. Such high frequency of 45x30 membrane has been observed twice during the experiments. Also very high frequency has been observed for l/b = 1.5 (60x40) membrane. Whether this is accidental or is character of l/b = 1.5, and to establish exact nature of variation of frequency during post-flutter, further controlled experiments are needed.

4.1:7 Pressure Distribution Over Membrane:

Pressures over the membrane surfaces were recorded and pressure coefficients non-dimensionalised with respect to undisturbed upstream dynamic pressure are plotted in Figures 10 to 12. The representative pressure distributions presented here have been selected to illustrate change in pressure over a fluttering membrane.

Figure 11 shows pressure distribution over lower surface of 45x30 membrane before and after flutter onset, when it is held in centre of the test section. There is a considerable change in pressure over the membrane after flutter onset and hence in its deformation. But the plot does not give information about the nature of flutter, because the flutter being travelling wave type, deflection of membrane will change from point to point with time and hence the pressure at corresponding points.

In Figure 12, pressure distribution over upper and lower surfaces of the membrane during flutter are plotted when it was placed in the centre of test section. Difference in C_p distribution at a point over and below the surface of membrane indicates different deformation at that point at different times. This plot gives some information about cross stream deformation of the membrane also. Putting more number of pressure tubes in cross stream direction may help in getting more information and nature of flutter.

4.2 Conclusions

Flutter problem of a membrane having moveable boundaries is studied at low speeds. Results of present study are:

Flutter of a membrane is of travelling wave type. The critical speed and the amplitude of oscillations and hence the deformation of membrane depends upon its edge conditions.

Critical speed of membrane varies with its length-to-width ratio but the rise or fall in speed seems to depend upon the manner in which l/b ratio is achieved.

Critical speed was greatly influenced by the width of the membrane.

Inplane tensions had the favourable effect of raising the critical speed. Flutter frequency also increased with tension. Rate of increase of speed with tension was dependent on size of the membrane. Inplane tension limited the amplitude of oscillations.

Among the membranes having same l/b ratio, the smaller ones fluttered at higher speeds. Flutter frequency raised with decrease in size for $l/b < 1.0$ whereas for $l/b > 1$ it was low for smaller sizes.

Solid wall lowered the critical speed as its distance from the membrane was decreased. It also reduced the deflection of membrane.

As the speed of air flow over the membrane was increased beyond onset value, the frequency of oscillations increased.

4.3 Recommendations for Further Work

Subsonic flutter investigations may be of interest in problem of panel flutter of flexible or inflatable structures at low speeds. A preliminary attempt to gather information about membrane flutter has been made but because of the complicated travelling wave flutter, further work remains to be done to understand this problem area more fully. More carefully controlled experimental techniques and improved instrumentation will be needed for this.

As a first step, the tunnel speed control system is to be improved.

In the present work, effects of tension in streamwise direction alone have been studied. Further experiments can be carried out with tension along the cross stream direction or along both the directions.

To explain few of the points of present work more clearly, extensive parametric studies have to be conducted.

Effect of porosity of the membrane can be studied.

Improved and systematised strain gauge techniques will give better frequency results and help understand the phenomenon more clearly. It may help in finding the stresses in membrane during flutter.

Pressure survey technique does not seem to be much helpful in giving information about travelling wave flutter and its characteristics. As an alternative, flow visualisation techniques should be improved.

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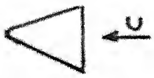
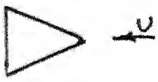
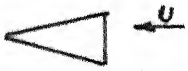
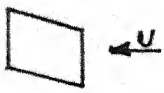
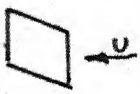
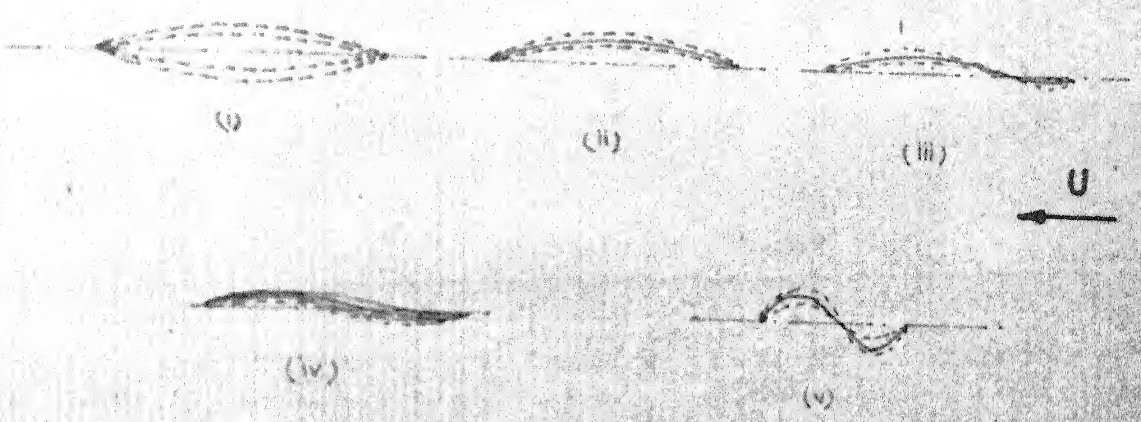
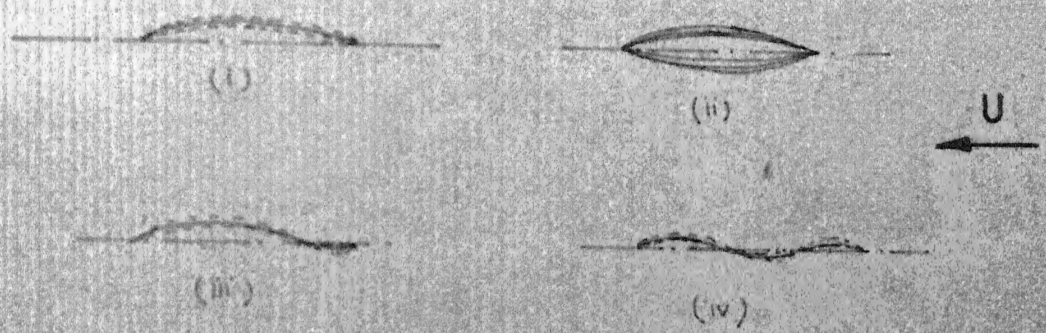
TABLE 1 : CRITICAL SPEED AND FLUTTER FREQUENCY AT T_1

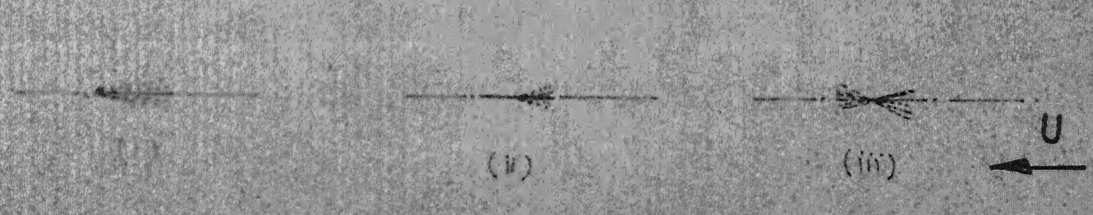
Shape	Size	Orientation	U_{cr} (m/sec)	f(c/s)
Triangular	30x30x30		21.20	35.83
			22.20	25.00
	25x25x25		19.20	33.33
			21.30	17.50
	35x35x27		21.52	26.00
			28.20	17.66
Skew	30x30; 10°		24.25	24.00
			24.32	27.66
	25x25; 15°		21.35	25.33
			20.60	35.00



SKETCH NO 1



SKETCH NO 2



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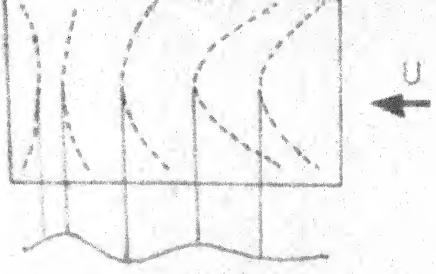

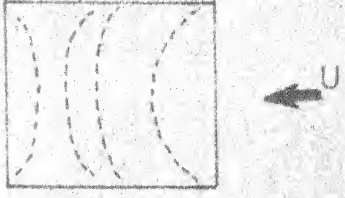

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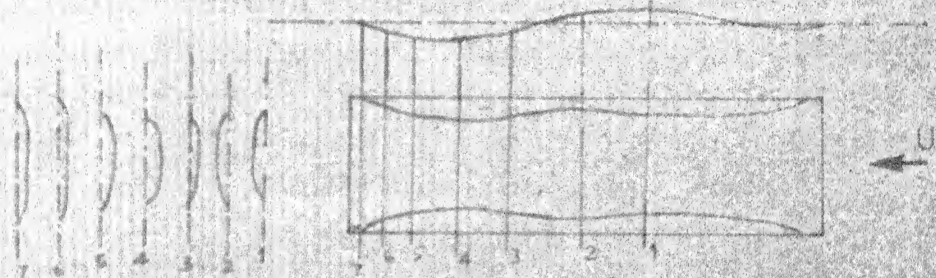

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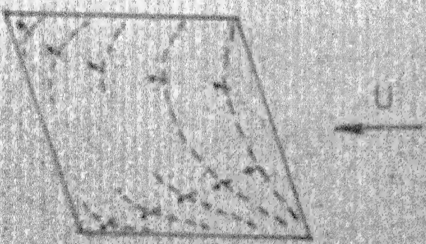
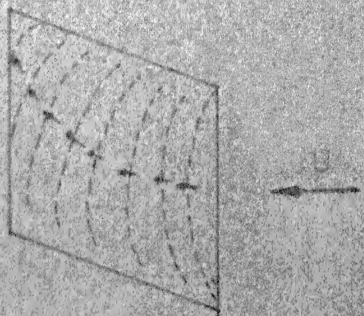
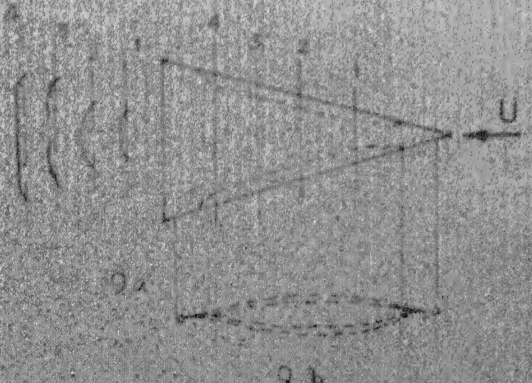
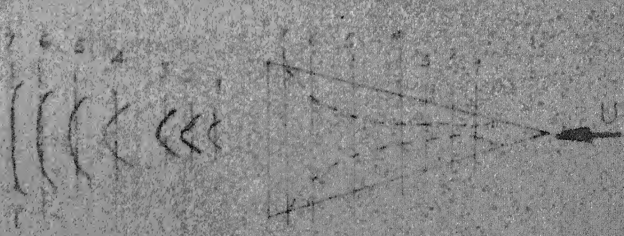




SKETCH NO 7

SKETCH NO 8





SKETCH NO 9

SKETCH NO.10

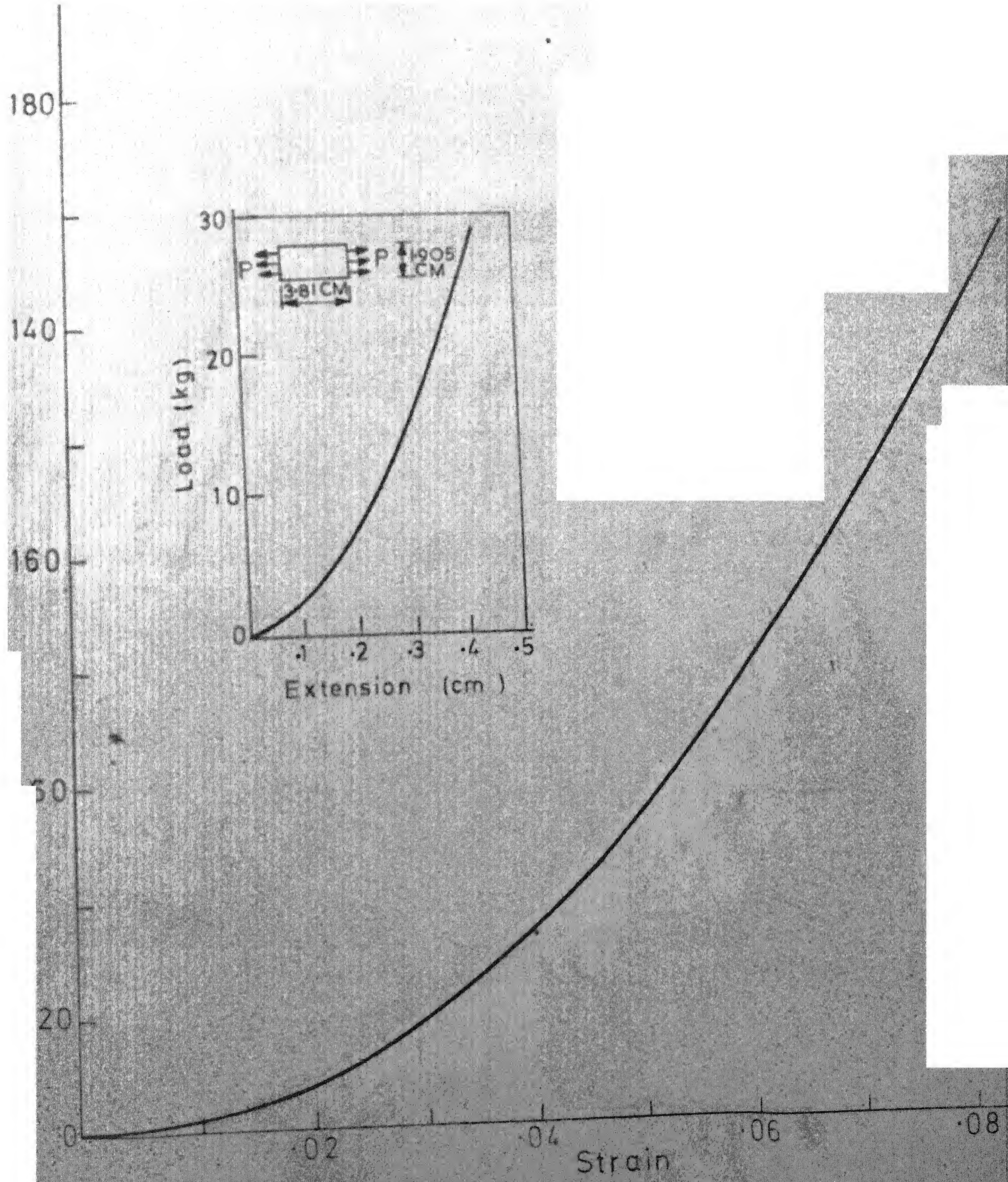


FIGURE 1 LOAD-DEFLECTION AND STRESS-STRAIN CURVES FOR THE MEMBRANE USED

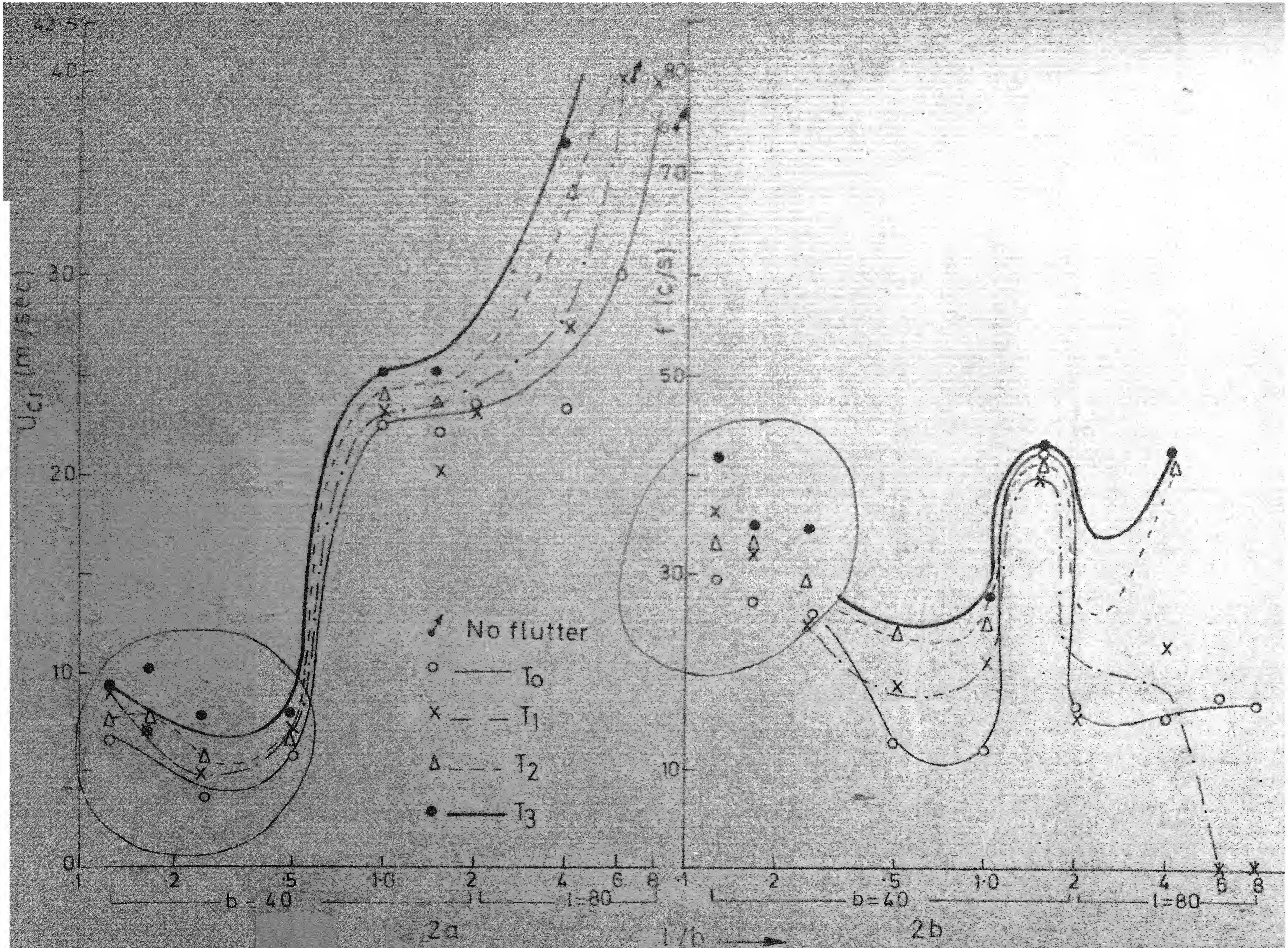


Figure 2 Variation of critical speed and flutter frequency with l/b ratio

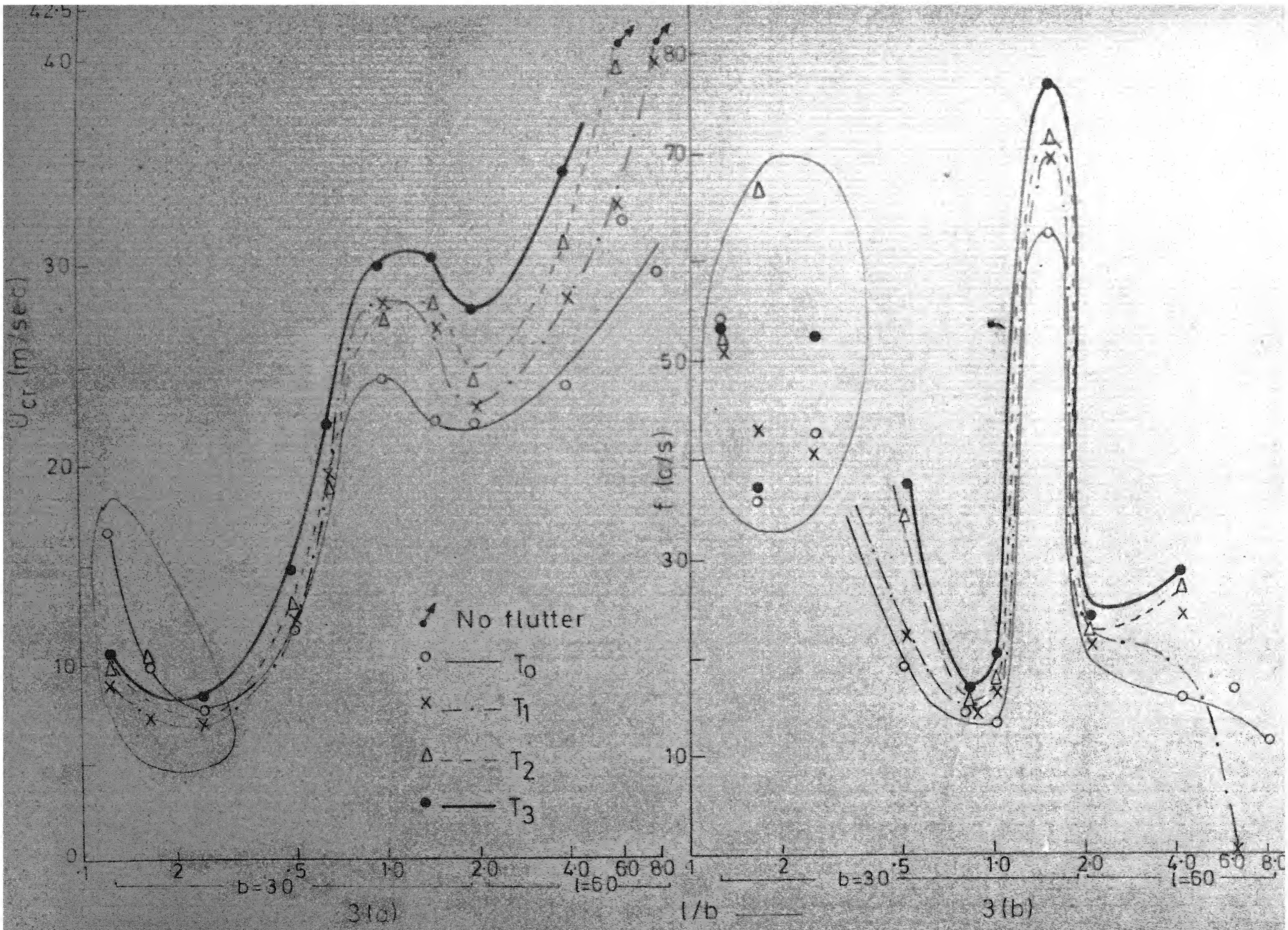


Figure 3 Variation of critical speed and flutter frequency l/b ratio

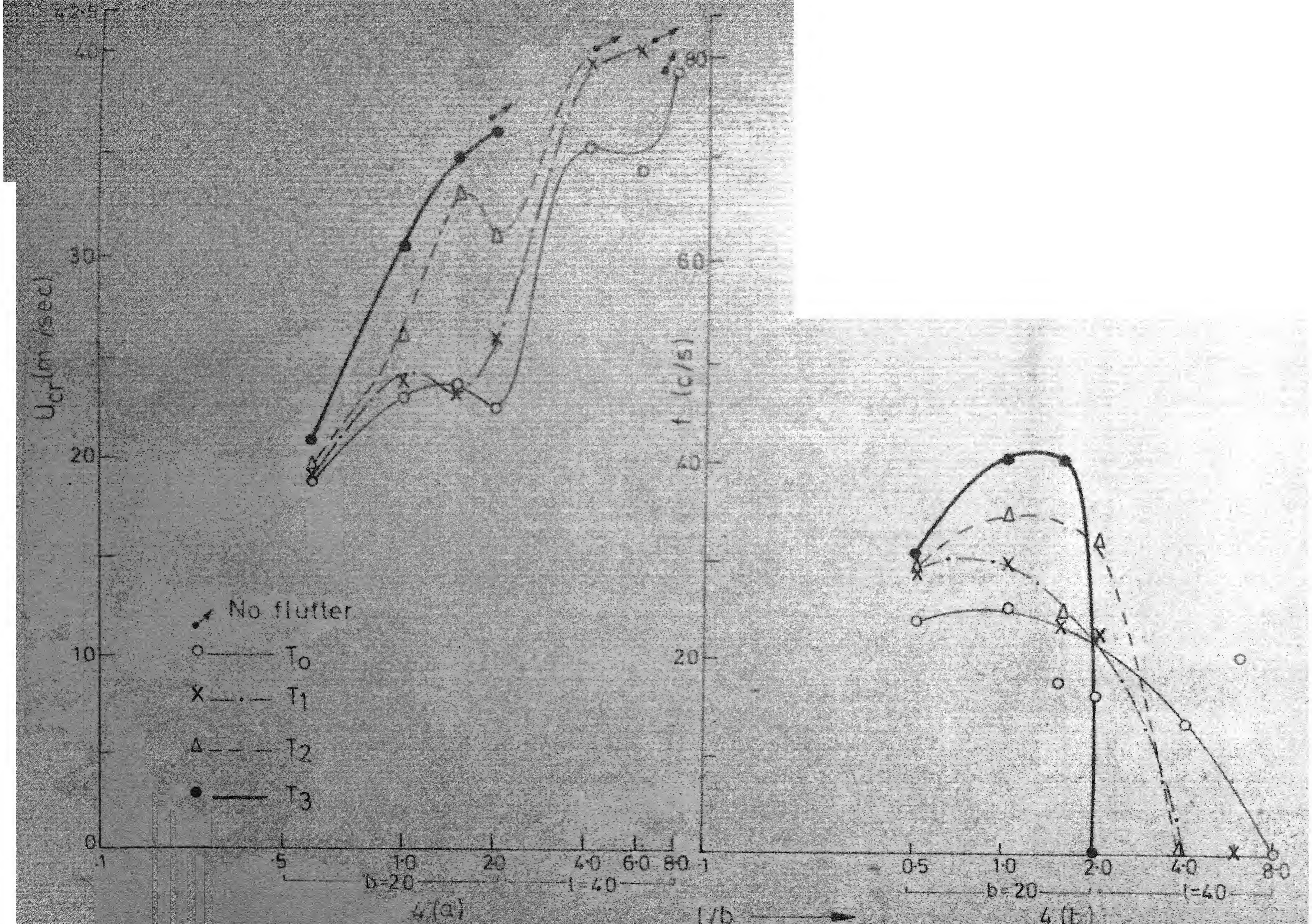


Figure 4 Variation of critical speed and flutter frequency with l/b ratio

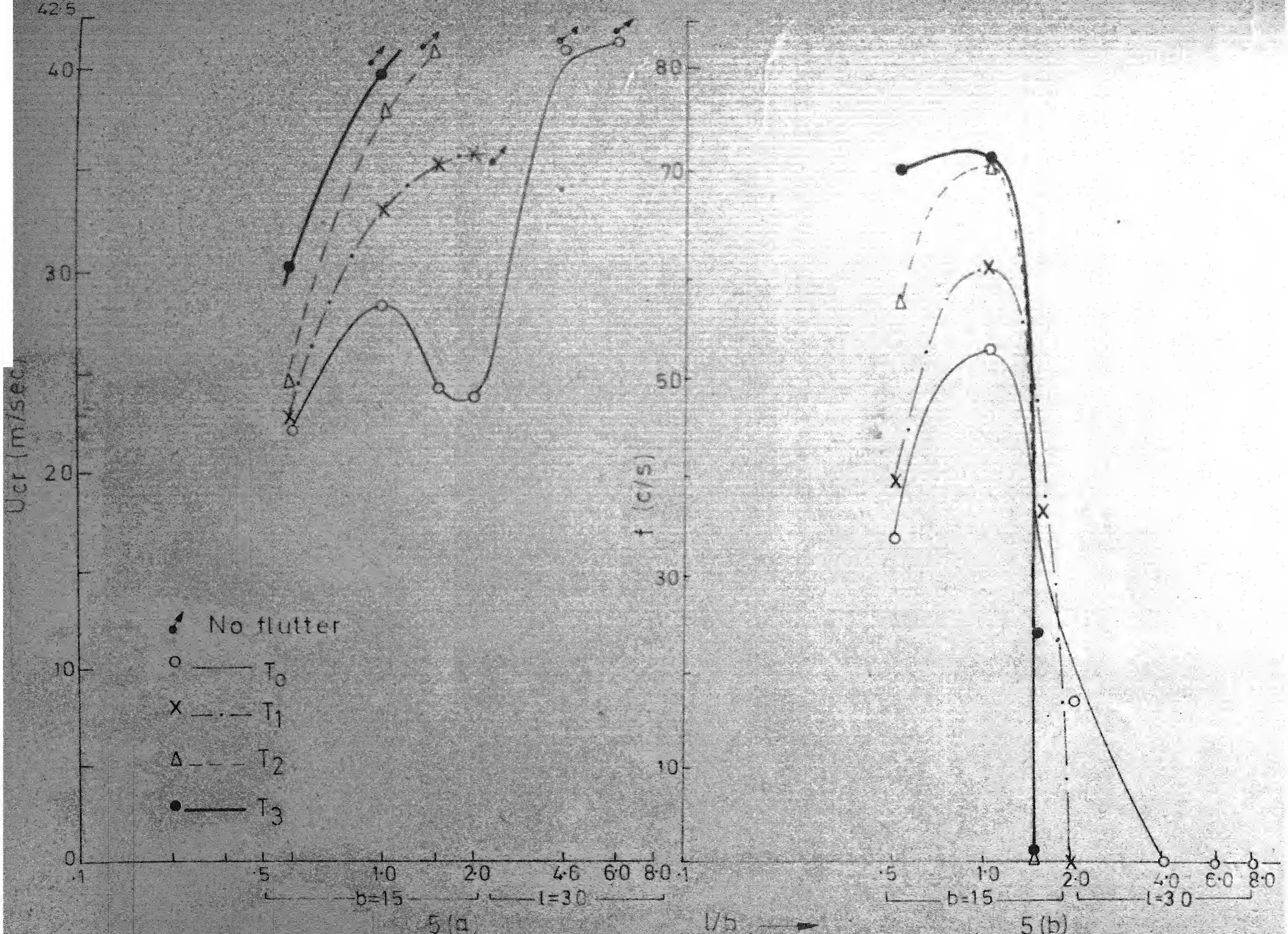
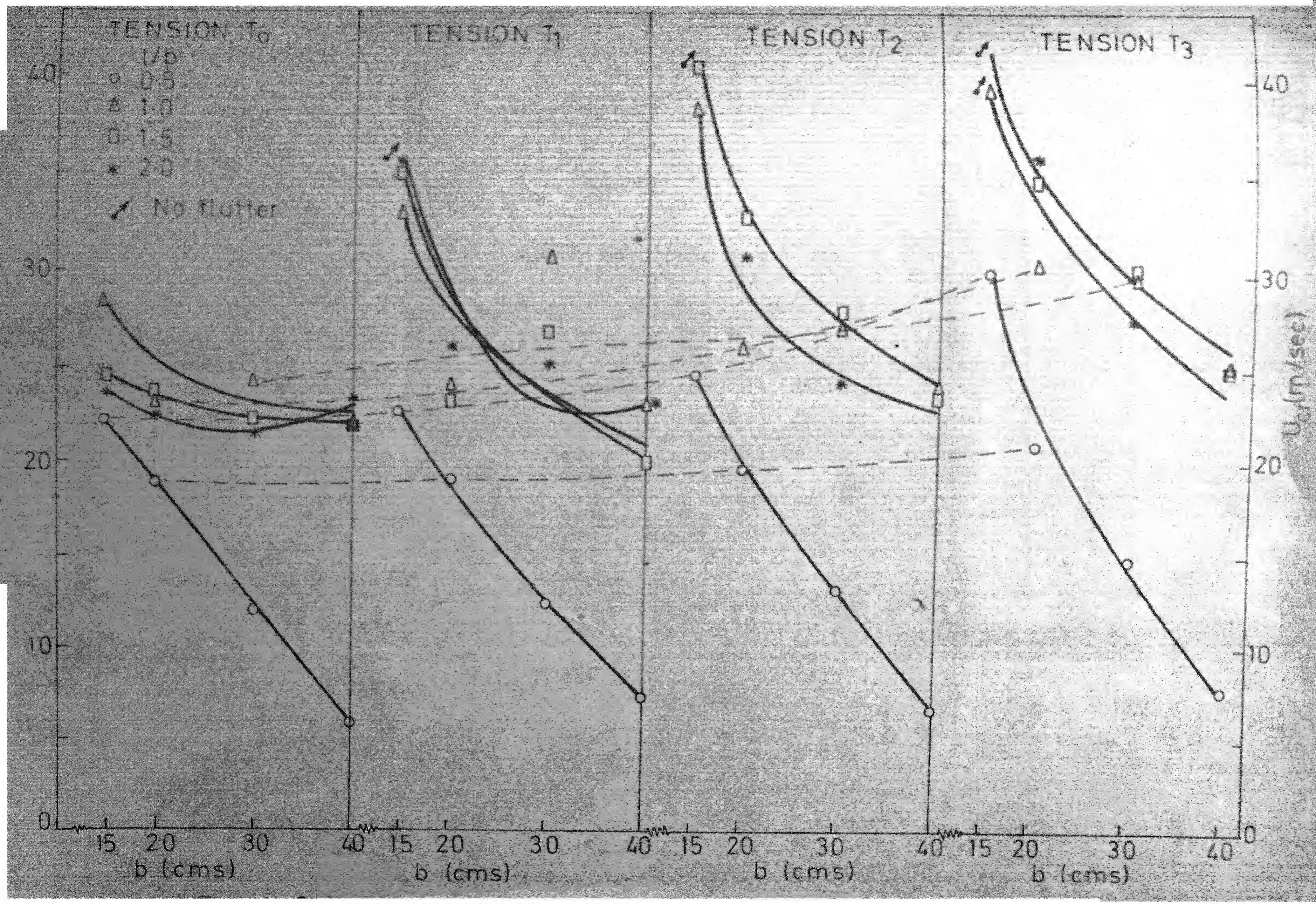


Figure 5 Variation of critical speed and flutter frequency with l/b ratio


TENSION T_0
l/b
0·5
1·0
1·5
2·0
No flutter
TENSION T_1
TENSION T_2
TENSION T_3
U_{cr} (m /sec)
U_{cr} (m/sec)
b (cms)

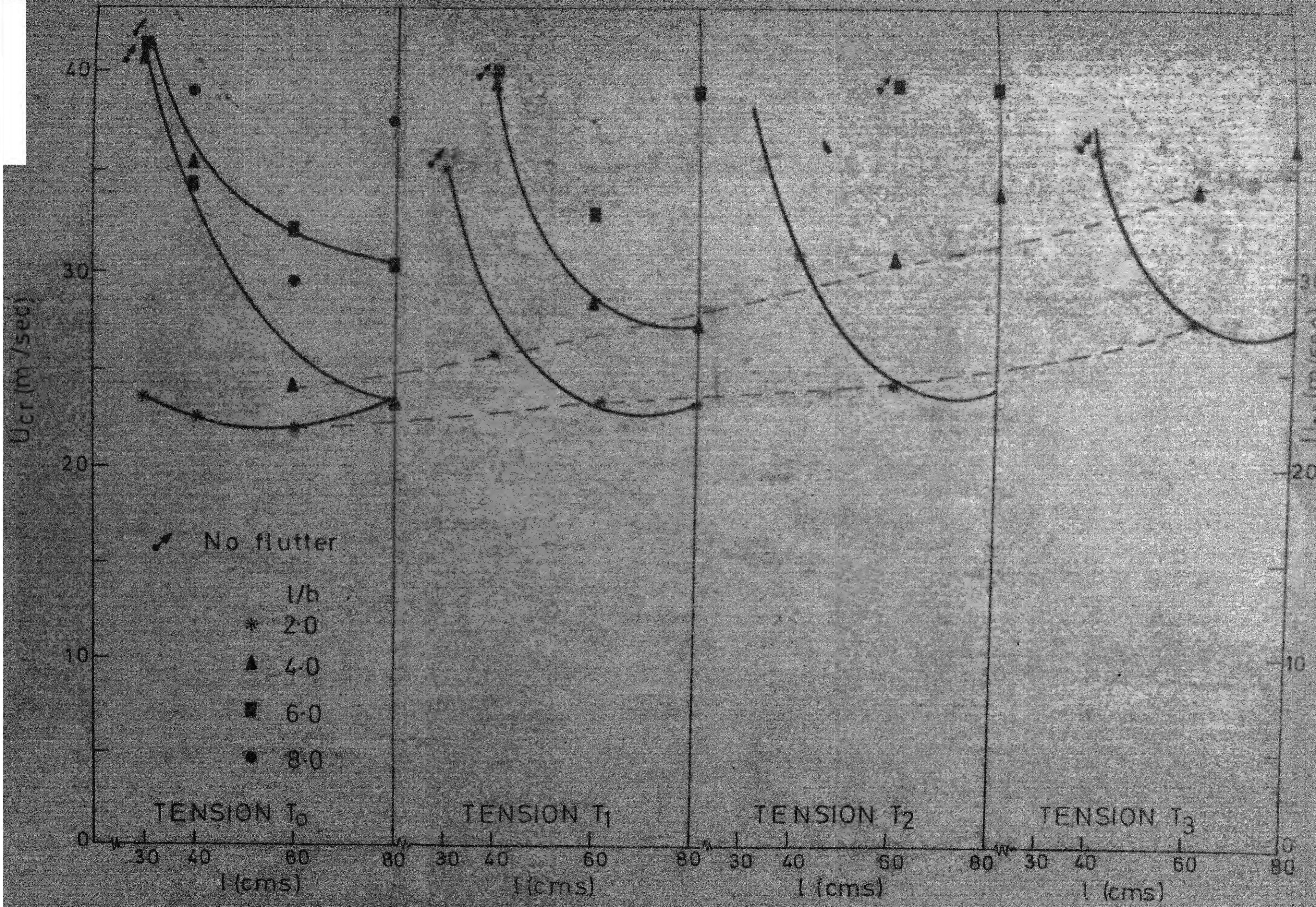
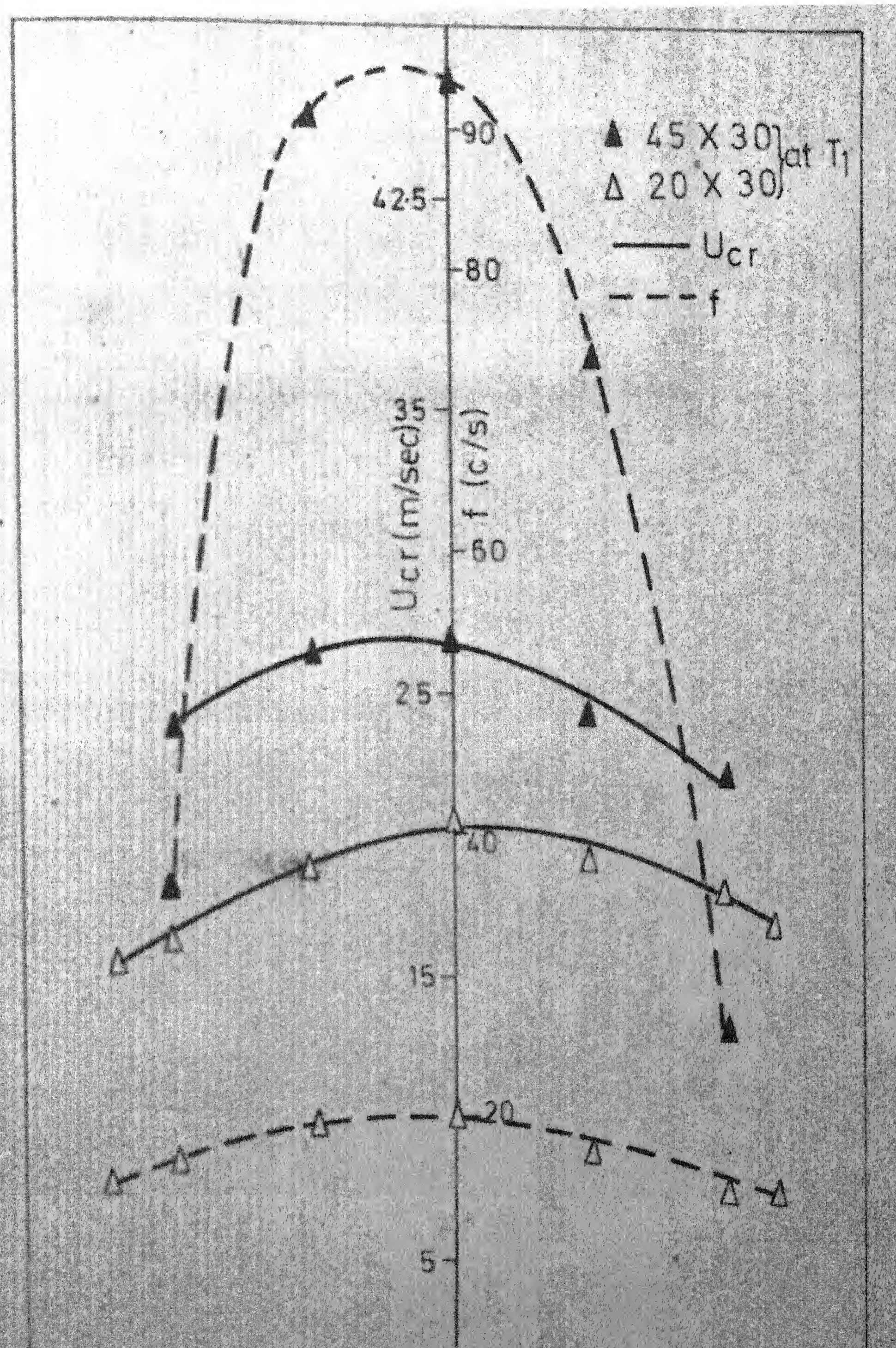


Figure 7 Variation of critical speed with length



Distance along height of test section (cms)

Figure 8 Effect of solid wall on critical speed and flutter frequency

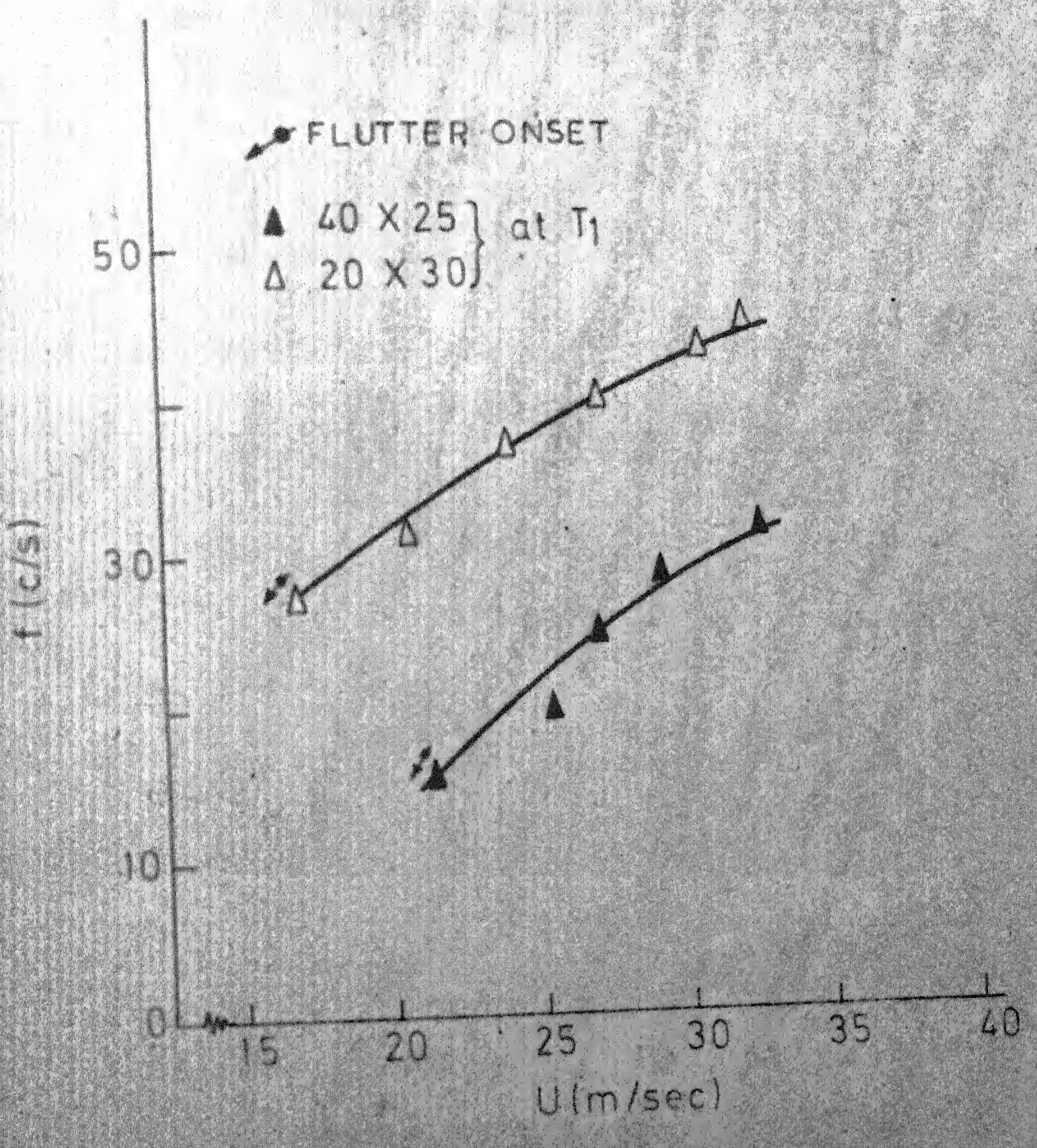


Figure 9. Variation of frequency with speed during post-flutte

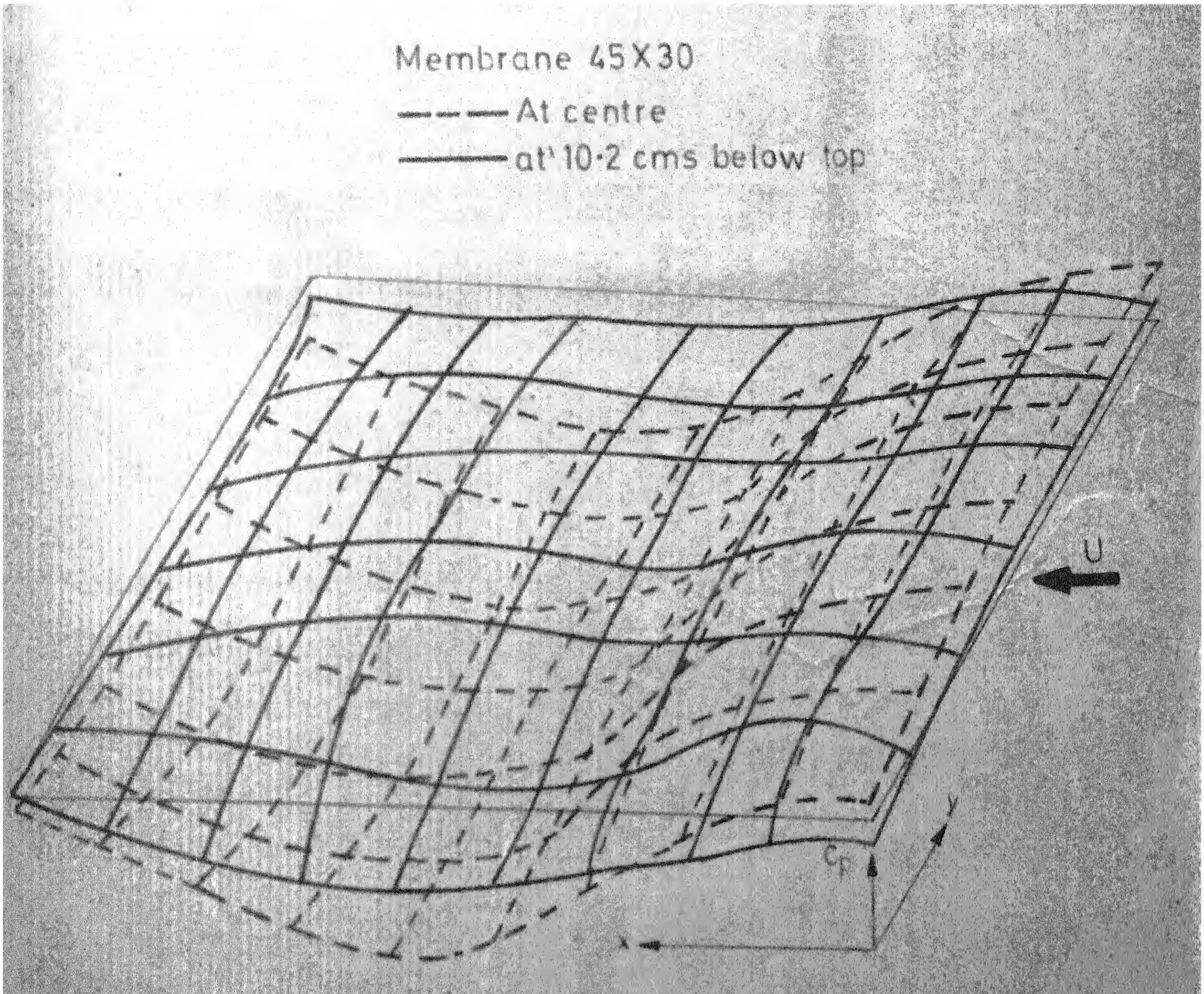


Figure 10 Pressure distribution before flutter over the lower surface of the membrane

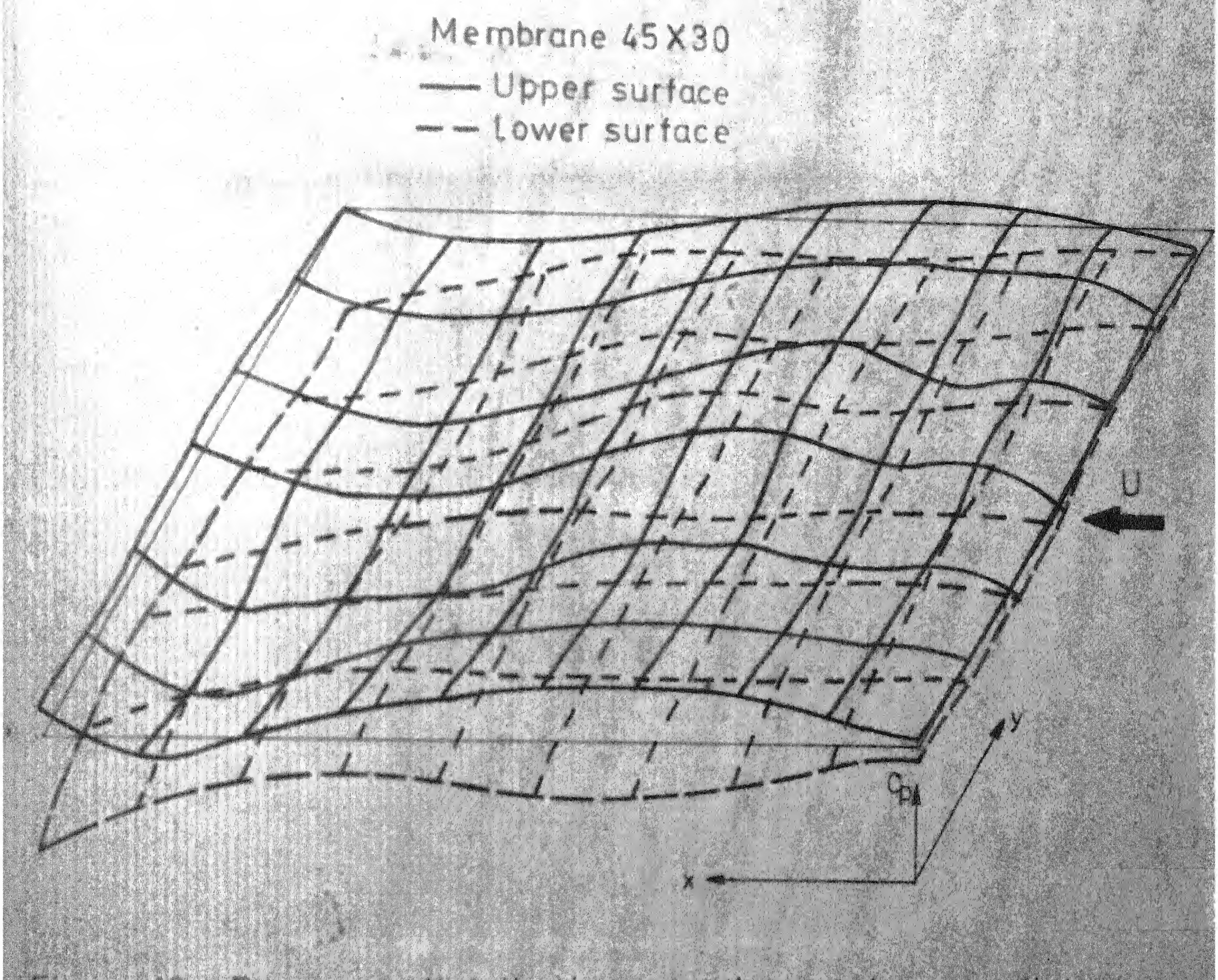
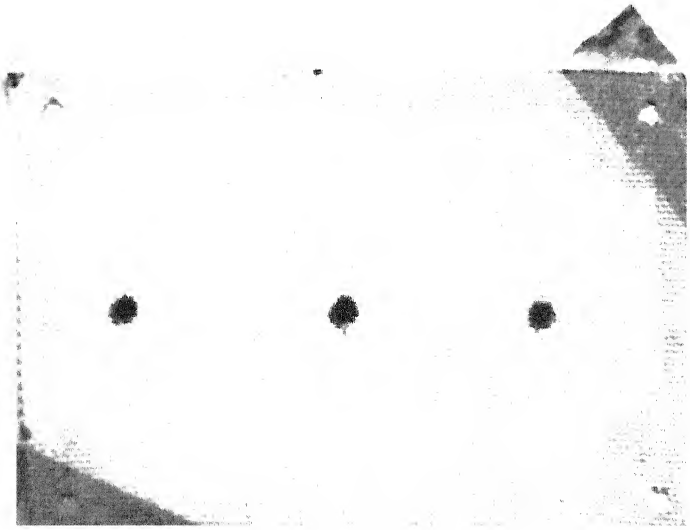


Figure 12 Pressure distribution over the membrane at flutter



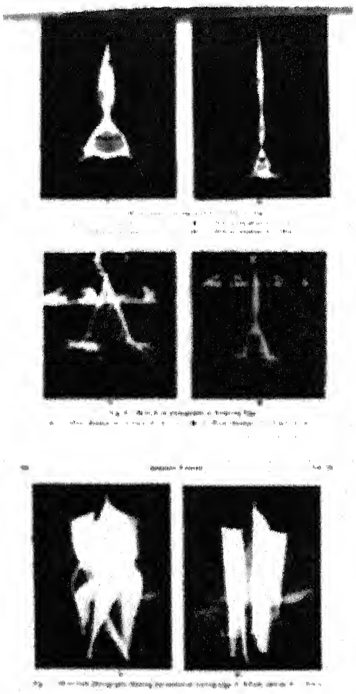


Plate 1

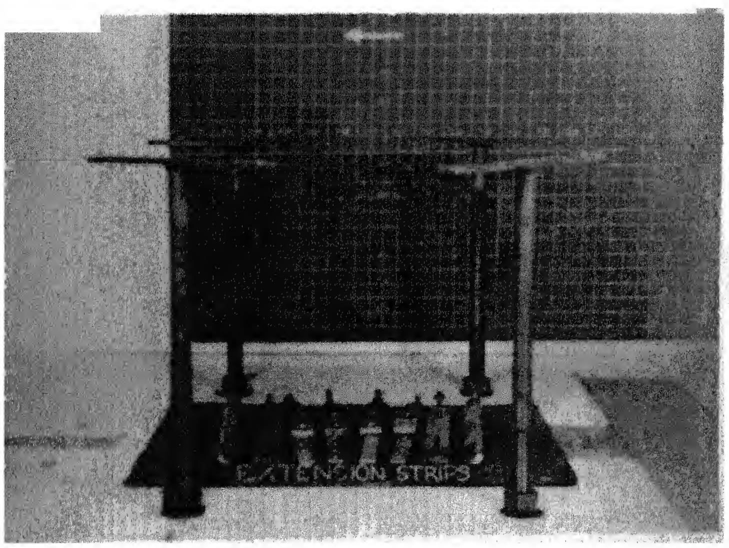


Plate 2

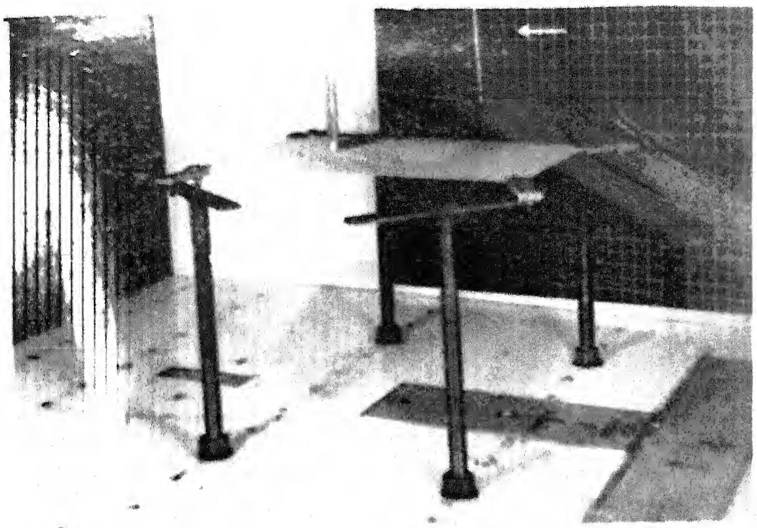


Plate 3

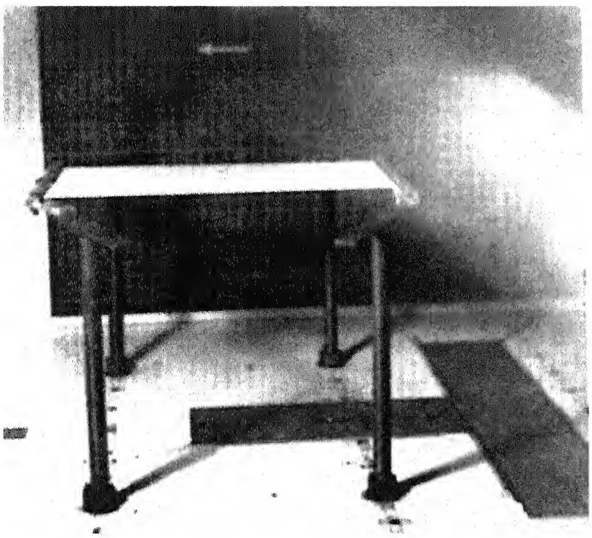
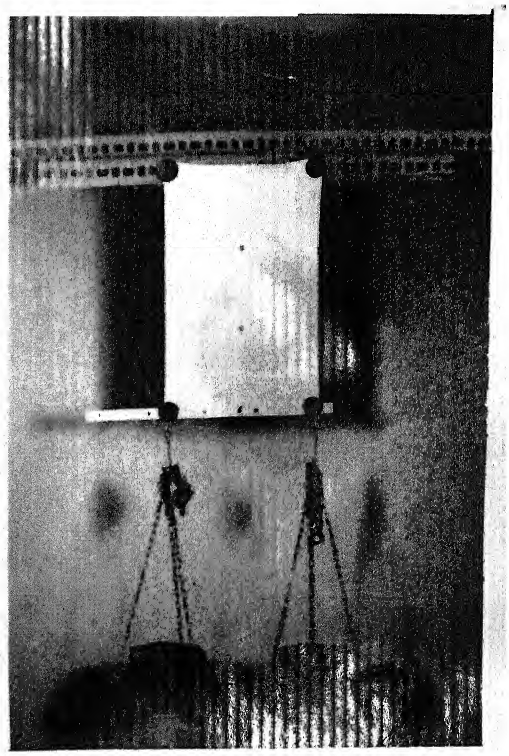


Plate 4

Plate 5



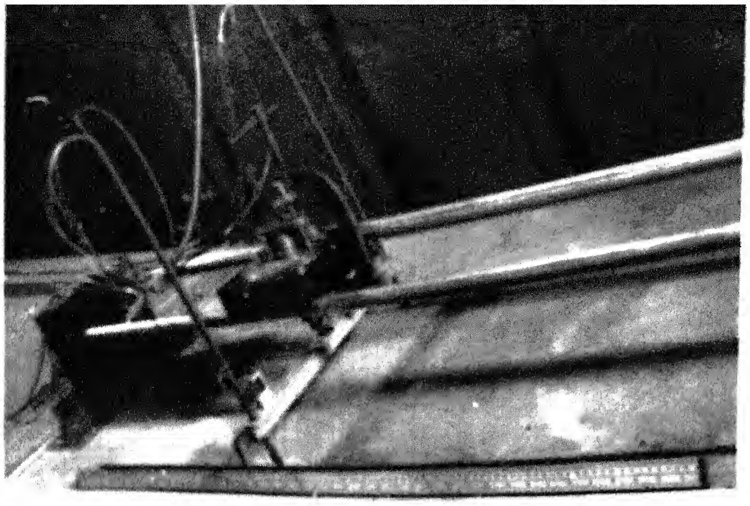


Plate 6

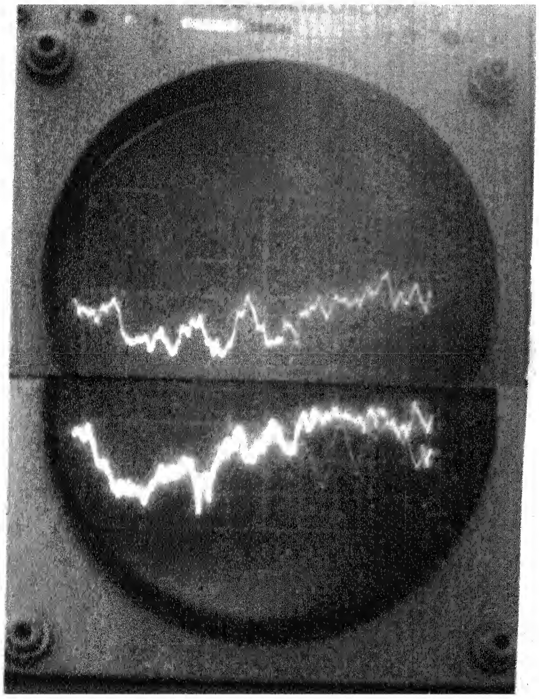
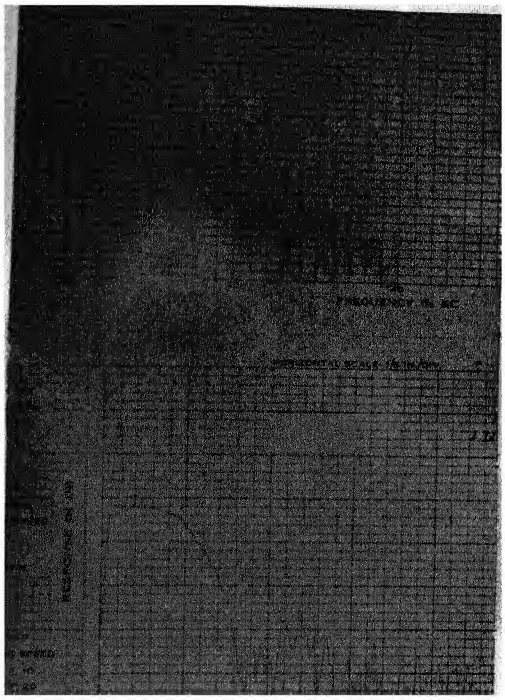


Plate 7



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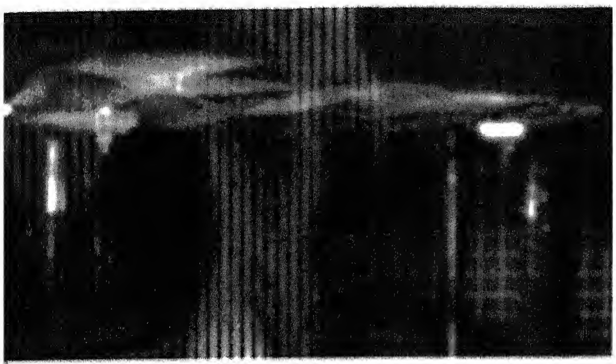
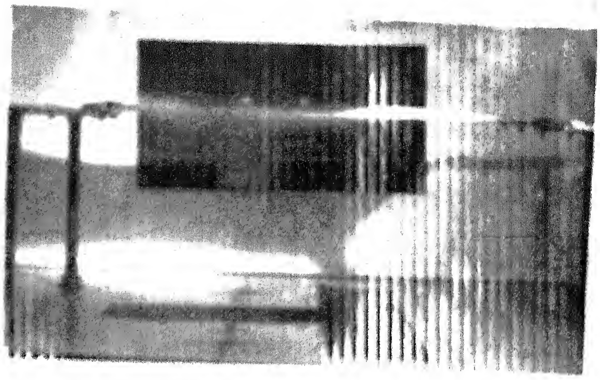


Plate 9



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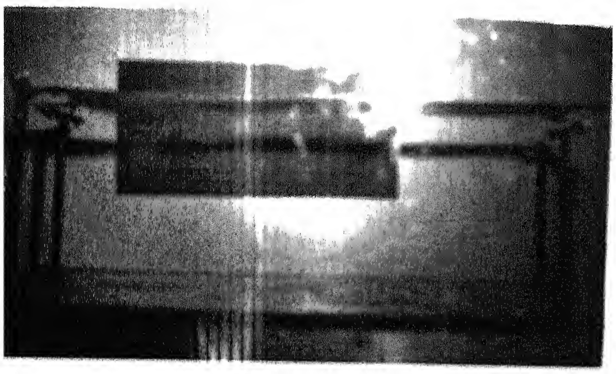


Plate 11

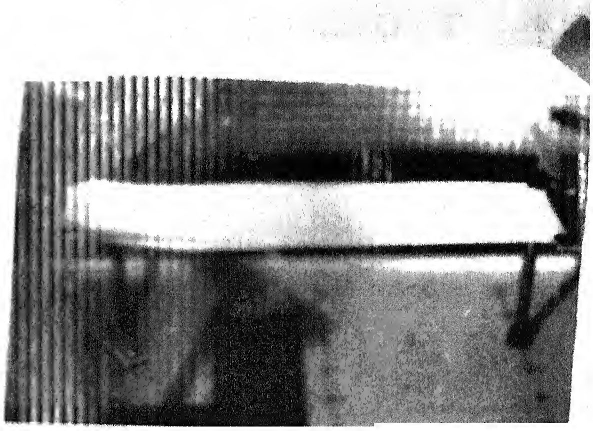


Plate 12

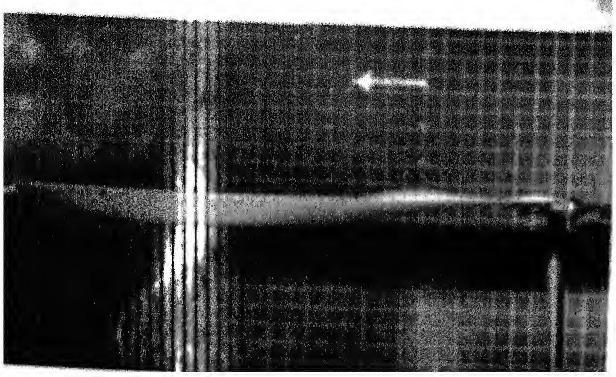


Plate 13

Plate 14

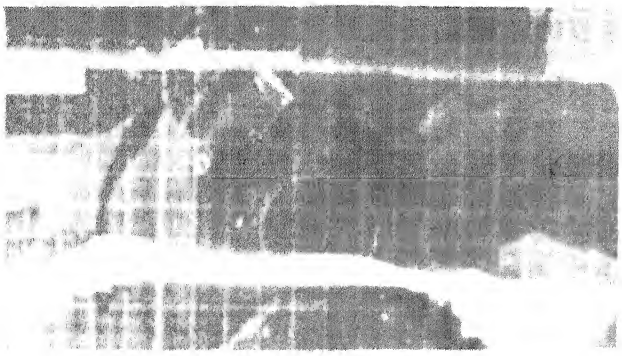


Plate 15

Plate 16

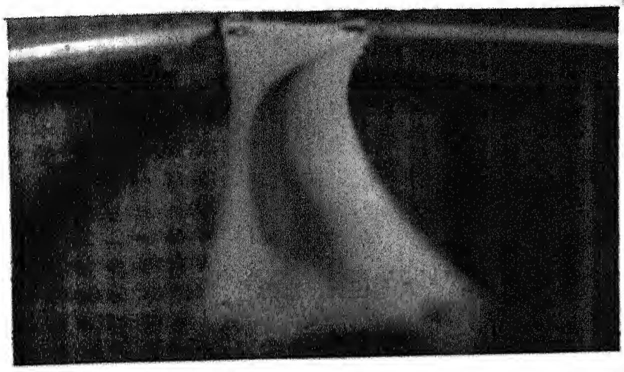


Plate 17

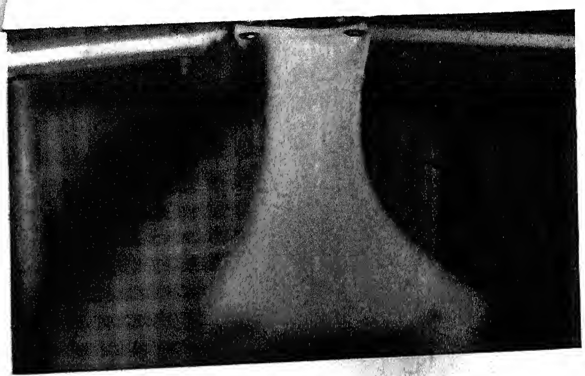


Plate 18

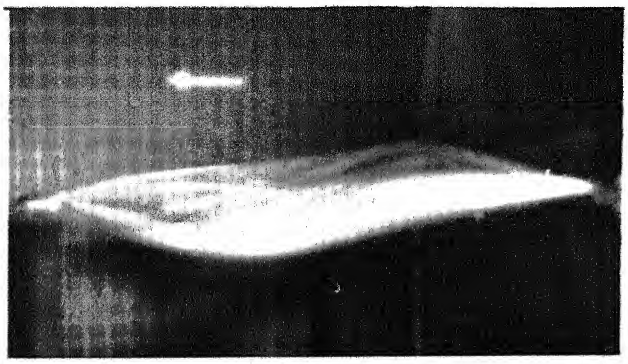


Plate 19

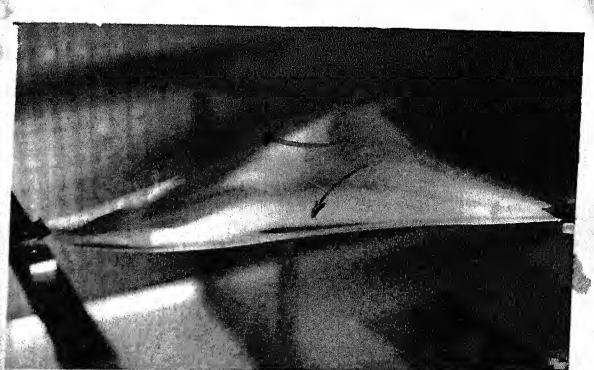


Plate 20

Plate 21

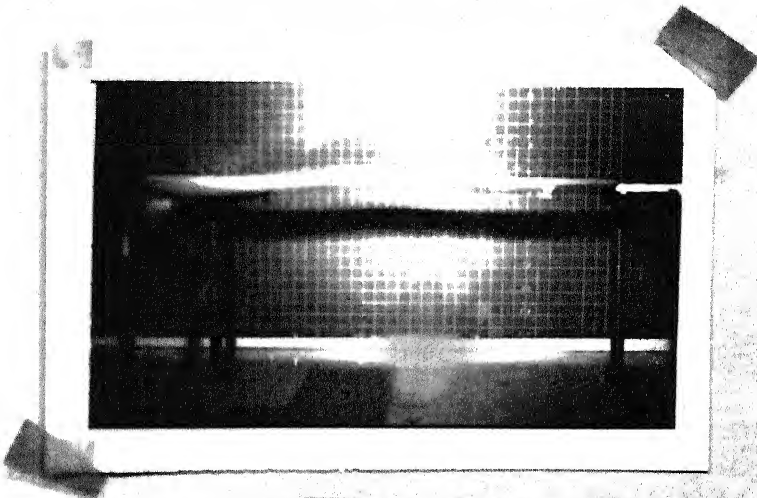
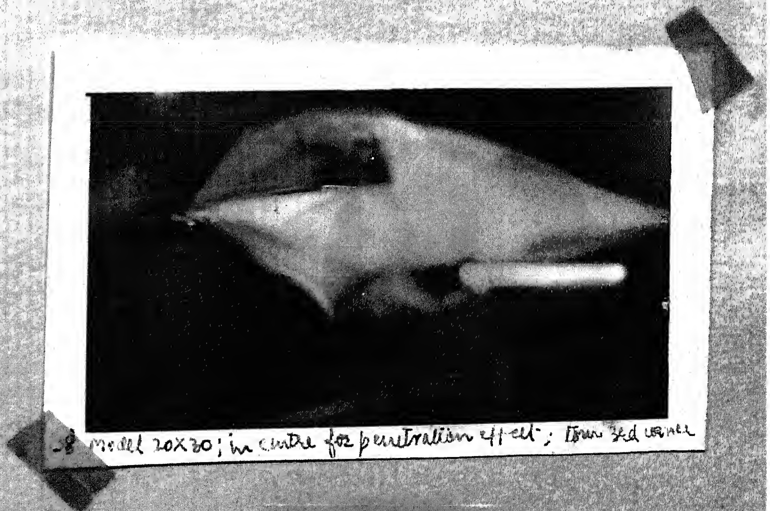


Plate 22



-8 Model 20X30; in centre for penetration effect; from 3rd corner

Plate 23